STEM BREAKAGE OF *PINUS RADIATA* DURING MECHANICAL FELLING IN KINLEITH FOREST, CENTRAL NORTH ISLAND, NEW ZEALAND.

A report

submitted in partial fulfilment

of the requirements for the Degree

of

Master of Forestry Science

in the

University of Canterbury

by

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University of Canterbury

1996

ABSTRACT

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STEM BREAKAGE OF *PINUS RADIATA* DURING MECHANICAL FELLING IN KINLEITH FOREST, CENTRAL NORTH ISLAND, NEW ZEALAND.

By Michael Lambert

This report examines stem breakage of *Pinus radiata* as a result of mechanical felling in Kinleith forest. Four machines were studied, two Bell TF120 feller-bunchers and two Timbco T445 hydro-bunchers.

The machines broke between 84% and 100% of the trees felled. Most causes of breakage could not be determined. Of that which could, falling trees striking stumps and previously felled logs accounted for the majority of the breakage.

The machine operators and the machine types studied were deemed to be significantly different and thus separate breakage functions were derived for each operator and machine type. The breakage function currently used by Carter Holt Harvey Forests Kinleith, produced from manual felling data, was compared with the newly developed mechanical functions and found to be different. For this reason a mechanical breakage function was created.

Nested analysis showed that most of the variation in relative break heights was due to differences in individual trees, not differences in machines or differences in operators.

Two sets of statistically significant equations between height and machine type and the breakpoint variables diameter at the break point and relative break height were identified. Although the models account for some of the breakage, none of the relationships developed completely explain how the variables influence stem breakage. Further research is required into operator and the landing environment variables and how these affect felling breakage.

ACKNOWLEDGMENTS

I would firstly like to thank Michelle Looney and other Carter Holt Harvey Kinleith staff for their support and guidance throughout the course of this project.

Special thanks also to the harvesting crews I worked with during the summer. Thank you to W.R Duncan and Gang 31, McDonald & Brightwell Ltd. and Gang 33, McDermitt Logging and Gang 6 and RMD Logging and Gang 38.

I would also like to express my gratitude to Ron O'Reilly, Kevin Boston and Richard Woollons for their assistance during the data analysis and discussion stages of this report.

Finally I would like to thank Wayne Anderson for his insights and help during the data collection.

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CHAPTER ONE

INTRODUCTION

1.1 GENERAL INTRODUCTION

This paper reports on the stem breakage of *Pinus radiata* during mechanical felling in Kinleith forest, Central North Island, New Zealand.

In harvesting, felling is the first step in the process of taking timber to the customer. Standing timber has only potential value; the actual value is determined by the end products. Realisation of this value is dependant on recovering all of the available wood value from the stand. Murphy (1989) found value recovery to be highly dependant on the amount of felling breakage incurred during harvesting. Conway (1978) attributed around forty percent of the total value lost in all forest operations to the felling stage. Loss was through either stem breakage or high stumps. This highlights the importance of felling and the influence it has over later stages in the cycle, and ultimately wood value.

Many studies have investigated breakage of *Pinus radiata* as a result of motor-manual falling. Manual fallers have the ability to direct trees to fall in favourable lays through the use of wedges, jacks, strategic cuts and other methods. However they have no real control over the speed at which trees fall. Twaddle (1987) believed little could be done to prevent stem breakage using the traditional manual methods although he felt directional felling could reduce the damage.

There appears to have been little investigation into stem breakage caused by mechanical fallers despite their increased presence in New Zealand forest operations. Many mechanical harvesting crews believe they cause less breakage than other crews[1]. Their beliefs are based on personal observations and the reduction in drags of "shorts"

[1] Personal Communication: Harvesting gang owners, foremen and faller operators, Carter Holt Harvey Forests (Kinleith), November 1995.

(small pieces of log) that are necessary each week.

Over the past decade or so, mechanical felling machines have been used to fell radiata in New Zealand. These machines have greater control than manual felling on how and where trees land. This greater control could be expected to result in reduced stem breakage. This will be investigated during the course of this study.

Conway (1978) and Yeoman (1994) listed a number of advantages of mechanical harvesting. Some of the main advantages are:

1. Cutting production is improved with most mechanised fallers.
2. Skidding production is increased through greater stem alignment.
3. Wood utilisation is improved because of lower stump heights (and possibly through reduced breakage).
4. Mechanised falling provides more protection for people working at the felling face.

However mechanised harvesting also has disadvantages when compared to manual felling. The main ones include:

1. Limited manoeuvrability of the machines on adverse slopes and broken ground.
2. Purchasing cost.
3. Limited size range that some machines can safely handle.

1.2 KINLEITH FOREST

Currently Carter Holt Harvey Kinleith use a standard breakage function derived by Piebenga (1989) in their MARVL operations. The function currently states that trees break at 68% of their height. This breakage function is used for both hauler and groundbased systems, including mechanical harvesting. It was derived from data collected from manual felling operations, and as such may have become dated with the increased presence of mechanical felling. The breakage function used has a direct relationship with the average break height of a tree which in turn affects the "quality percent".

ie quality percent = quality tonnes / (quality + pulp tonnes).

This has become important in harvesting due to the new differential payment system currently used by Carter Holt Harvey Forests (CHHF) Kinleith.[2] The greater the "quality percent" the greater the payment.

1.3 NATURE AND SCOPE OF STUDY

This project has four main objectives, these being:

1. To assess whether there is any significant difference between two different mechanised fallers, the Bell TF120 and the Timbco 445 and between the operators of the different machines.
2. To derive breakage functions for the separate machines where any differences are deemed to be significant.
3. To determine whether there is any difference in the relative break heights between manual and mechanical felling methods*. If there is a difference, a separate mechanical breakage function will be developed.
4. To assess which variables (diameter at breast height[3], height, change in slope, machine type) affect breakage in mechanised falling. Using such tree and stand details an attempt at a predictive breakage equation will be made.

*Comparison will use Piebenga's 1989 breakage function for 20-28 year old *Pinus radiata* felled manually in Kinleith forest.

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[2] Personal Communication: Michelle Looney, Regional Planning Group, CHHF (Kinleith), November 1995.

[3] Diameter at breast height (dbh) is measured at 1.40 metres up the tree.

CHAPTER TWO

REVIEW OF THE LITERATURE

Numerous attempts have been made to study felling breakage in *Pinus radiata.* Through these studies various breakage functions and theories have been put forward in an attempt to predict break heights and the amount of breakage. The literature review will concentrate on the findings from studies of *Pinus radiata* as this is the species of interest in the current study. However, it must be recognised that some studies have been completed on other species such as Corsican pine and Douglas-fir.

2.1 BREAKAGE FUNCTIONS

Breakage functions are used to estimate the break point of an individual tree through using either tree height or diameter measurements, or both. Many functions have been produced for *Pinus radiata* from different parts of New Zealand.

Vatasan & Seymour, reported by Piebenga (1989), while working in Kinleith Forest in 1975, found a relative break height (the ratio of height to the first break to total tree height) of 0.68.

Work during the 1970's in Kaingaroa Forest by Goulding & Deadman, reported by Manley (1977), also produced a relative break height of 0.68 for 40 year old trees.

Murphy & Gaskin (1982) studied breakage 41 year old trees in Whakarewarewa State Forest and produced the same relative break height of 0.68.

In 1983, Murphy, this time working in two New Zealand Forest Products Ltd. (NZFP) stands, found 0.686 and 0.708 to be the relative break height of the 30 and 48 year old trees respectively. Working the following year in Tairua forest with 43 year old trees, he found the relative break height to be 0.83.

Twaddle (1987) studied piece size characteristics of managed stands after felling in Kaingaroa and Kinleith forests. The 31 year old trees both produced similar results with a relative break height of 0.66 for the Kaingaroa data and 0.65 for Kinleith.

Piebenga (1989) reported on a study conducted by New Zealand Forest Products (NZFP) staff in 1988, which produced a relative break height of 0.67 and a mean relative break diameter of 0.44 for 34 year old trees. While working in Kinleith forest in 1989, Piebenga derived a relative break height of 0.68 and a relative break diameter of 0.42 for trees aged 20-28 years, and a relative break height of 0.776 and relative break diameter of 0.322 for 18 year old trees.

In 1995, Temple produced a relative break height of 0.76 for 26-28 year old trees in the Westland region.

Table 2.1 below highlights the various relative break heights determined for *Pinus radiata* in various locations.

TABLE 2.1: SUMMARY OF *PINUS RADIATA* RELATIVE BREAK HEIGHTS.

Author	Location	Relative Break Height
Vatasan & Seymour (1975)	Kinleith forest	0.68 (??yrs)
Goulding & Deadman (197?)	Kaingaroa forest	0.68 (40yrs)
Murphy & Gaskin (1982)	Whakarewarewa forest	0.68 (41yrs)
Murphy (1983)	????	0.686 (30yrs)
		0.708 (48yrs)
Murphy (1984)	Tairua forest	0.83 (43yrs)
Twaddle (1987)	Kaingaroa forest	0.66 (31yrs)
Twaddle (1987)	Kinleith forest	0.65 (31yrs)
NZFP (1988)	Kinleith forest	0.67 (34yrs)
Piebenga (1989)	Kinleith forest	0.68 (20-28yrs)
		0.776 (18yrs)
Temple (1995)	Westland	0.76 (26-28yrs)

The various figures produced by these studies indicate that breakage functions are fairly uniform (relative break height = 0.68) throughout New Zealand, although there are some variation in specific locations. Age appears to be a factor but only until a certain point after which any increase in age does not affect breakage. Determining where this point is exactly requires further investigation.

2.2 RELATIONSHIPS

In attempts to determine what factors affect breakage, researchers have endeavoured to find relationships between breakage and tree and stand details. At present no breakage equation exists that uses tree and/or stand details that will accurately predict where an individual tree will break.

Lee (1969) studied the breakage of *Pinus radiata* at clearfelling and its effects on sawlog yield. His investigations showed that mature radiata pine broke at a diameter approximately equal to half the dbh. He believed if a relationship between dbh and the diameter at the point of break was established this might be of value for estimating recoverable sawlog yield.

An investigation into factors affecting the breakage point of trees when felled was completed by NZFP staff at Kinleith in 1972. This unpublished report, supplied by CHHF Kinleith library, attempted to determine if the break height of *Pinus radiata* is related to other parameters such as dbh, total height, slope, upper stem diameters, basal area, tree volume, stems per hectare and tree form (vol./basal area). Using the diameter at the break point as the independent variable, logarithmic and non-logarithmic regressions were run with combinations of different parameters. Despite a large amount of data (750 data points), no satisfactory relationships could be determined. However from field observations, significant factors affecting breakage appeared to be operator 'effects', topography, the abundance of slash, stumps and other obstacles in the path of the falling tree and the green crown height.

Vatasan & Lockie's (1976) breakage study reported a large amount of variability in the percent breakage (the amount of breakage expressed as a percentage). This made analysis of the results very difficult. They attempted to relate the percent breakage to an independent variable such as age, height or dbh. As they expected, short fat trees had the least breakage while tall thin trees had the greatest. Poor relationships were derived from regression analysis between percent breakage and the independent variables. A multiple regression between percent breakage, height and dbh was tried. This produced an equation with a low degree of correlation, however it showed that breakage was more sensitive to changes in height than to changes in dbh. Percent breakage was also tested against the ratio of height/dbh, but this gave results which were not significant.

Manley (1977) studied felling breakage of Douglas-fir, Corsican pine and radiata pine at Kaingaroa and Whakarewarewa forests. He attempted to predict, for Douglas-fir and Corsican pine, the breakpoint of an individual tree on felling, given tree height and dbh and average compartment information on slope and stocking. Manley attributed much of the breakage to landing zone factors such as stumps, other stems and uneven ground. Due to the difficulties in quantifying these factors, operator variables and tree variables other than size, Manley was not able to predict the breakpoint of an individual tree more precisely than to say that relative break height for a species was approximately normally distributed with a certain mean and variance. For Douglas-fir, the relative break height mean was 0.745 with a standard deviation of 0.138. Corsican pine had a mean relative break height of 0.796 with a standard deviation of 0.103. Radiata pine produced a mean relative break height of 0.668 with a standard deviation of 0.134.

Murphy & Gaskin (1982) studied directional felling on steep country. Trees were felled downhill (crossed), downhill (parallel), across slope and uphill. The resulting relative break heights were very similar (~0.7) regardless of the felling pattern. The authors believed this indicated that slope, although significant, had a very small effect on break height. Despite the similar relative break heights they found that crossing logs, as well as drastic changes in slope and malformed trees, greatly affected the break heights.

Murphy (1983) studied breakage in two different aged stands owned by NZFP. He found there to be no significant difference in the incidence of felling breakage <u>or</u> the relative break height for trees in an old crop (48 years old) and new crop (30 years old) stand of similar height and dbh dimensions.

Murphy (1984) also studied felling breakage of *Pinus radiata* in Tairua forest. In this study, he found that tree size had a significant effect on stem breakage. Trees with smaller dbh had a greater probability of <u>not</u> breaking and their break points were higher than those with larger dbh. He found that slope steepness had no effect on the height a tree broke, rather breakage was the result of hitting obstacles such as stumps, other felled trees and sharp changes in slope. Murphy also felt that the trees in the study area had lighter crowns in comparison to trees from the Pumice Plateau and a higher wood density (>475kg/m^3). Thus the trees with lighter crowns would hit the ground with lower energy, therefore less force, resulting in reduced damage to the tree. Wood with higher density is also generally stronger, and Murphy concluded this may also reduce stem breakage. This may help to explain the high relative break height (0.83) he reported for this area.

Piebenga (1989) attempted to quantify breakage in felled *Pinus radiata* in Kinleith Forest. Of the breakpoint variables he regressed against dbh, height and both dbh and height, the stem diameter at the initial break point (dbp) produced the best relationship with R^2 values of 0.3540, 0.3333 and 0.3904 respectively. The multiple regression of dbh, height and dbp (0.3904) was highly significant at the 1% level. He produced two different breakage functions for two different age classes (20-28 years and 18 years). This may indicate a possible relationship between age and breakage, although he never tested this. However, Piebenga reported that the relative break heights and diameters did not vary significantly between the 20-28 year stands. Piebenga, like Murphy, felt that the nature of the tree landing zone was the most important factor determining breakage. He also reported that slope steepness had no effect on breakage, although his data were from a limited slope range (0° to -18°).

From these various studies it appears clear that the landing zone of a falling tree is an important factor affecting breakage. Landing zone characteristics such as the amount of brush materials on the site, the degree of ground undulation and the presence of stumps and logs all affect stem breakage. Other factors such as tree size, density, crown height/size and age also have roles to play but their effects seem less clear. As Twaddle (1987) remarked "other reasons for stem breakage, not yet fully understood, relate to the physical structure of *Pinus radiata* and the dynamics involved when a tree strikes the ground".

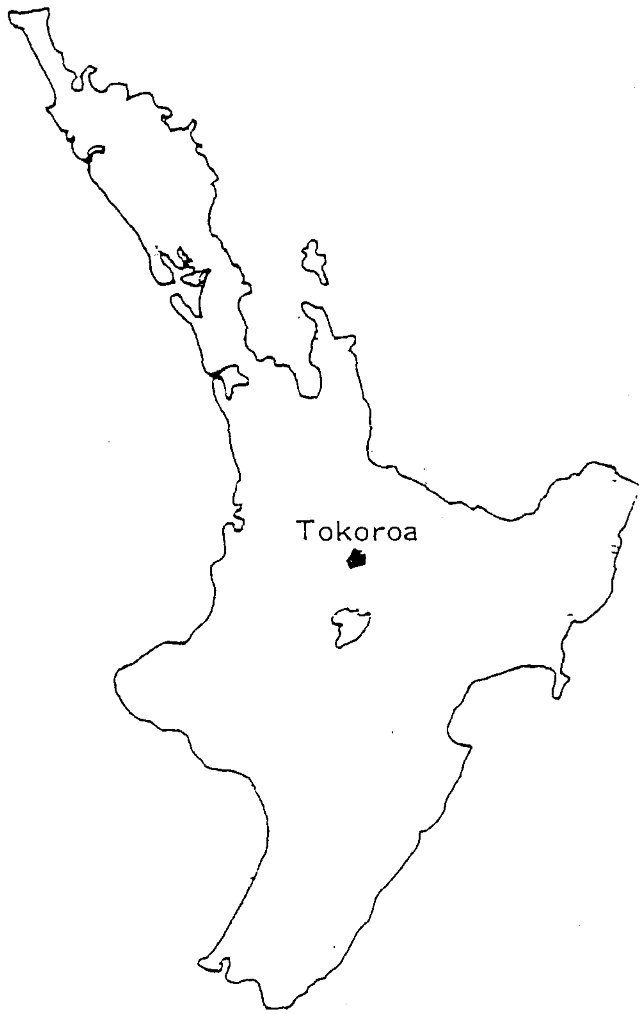
CHAPTER THREE

SITE DESCRIPTION

3.1 LOCATION

Kinleith Forest, situated in the central North Island of New Zealand, surrounds the township of Tokoroa, approximately 60 kilometres north of Taupo. The 130 000 hectare forest, owned and operated by Carter Holt Harvey Ltd., consists primarily of *Pinus radiata* with other species including eucalypts occupying less than ten percent of the land area.

Figure 3-1: Location Map



3.2 SOIL AND LANDFORM

The soils of the area are primarily podsolic or "pumice" soils derived from deposits of rhyolitic pumice. The characteristics of these yellow-brown pumice soils are a basal, gravelly layer of soft pumice with some stony fragments, a layer of pumice sand and a surface layer of pumiceous sandy silt. Fertility is generally low to medium. The topography is fairly broken with no distinct valley/ridge system evident.

3.3 CLIMATE

The climate over the Tokoroa-Kinleith region is reasonably mild with the mean annual rainfall of 1700mm spread fairly evenly throughout the year. The winter months tend to be wetter, and the summer months drier, than on average. The wind is predominantly from the South West, and often brings showers and rain to the area. Warm dry winds from the South East are also common.

3.4 HARVEST AREA INFORMATION

Bell One was operating in an area where the ground was slightly sloped (average slope ~3 degrees) but fairly broken. Old native logs were present but these were not a problem for this machine. Fairly heavy understorey growth was present which needed to be cleared to gain access to some trees. Bell Two was working in a much flatter area (average slope ~-1 degree). Major ground undulations were uncommon however heavy undergrowth was present in places. Timbco One operated in a stand which was again sloped (average slope ~5 degrees) with marked ground undulations. Old native logs, fences and heavy undergrowth were present throughout the stand. Considerable amounts of vine and creeper vegetation made felling difficult at times. As a result some hang-ups occurred. Timbco Two worked in a flat area (average slope ~-2 degrees) with limited undergrowth apart from treeferns and small shrubs. There was very little broken ground. The stand details and location are for each area are shown in Table 3-1 and Map 3-1 below.

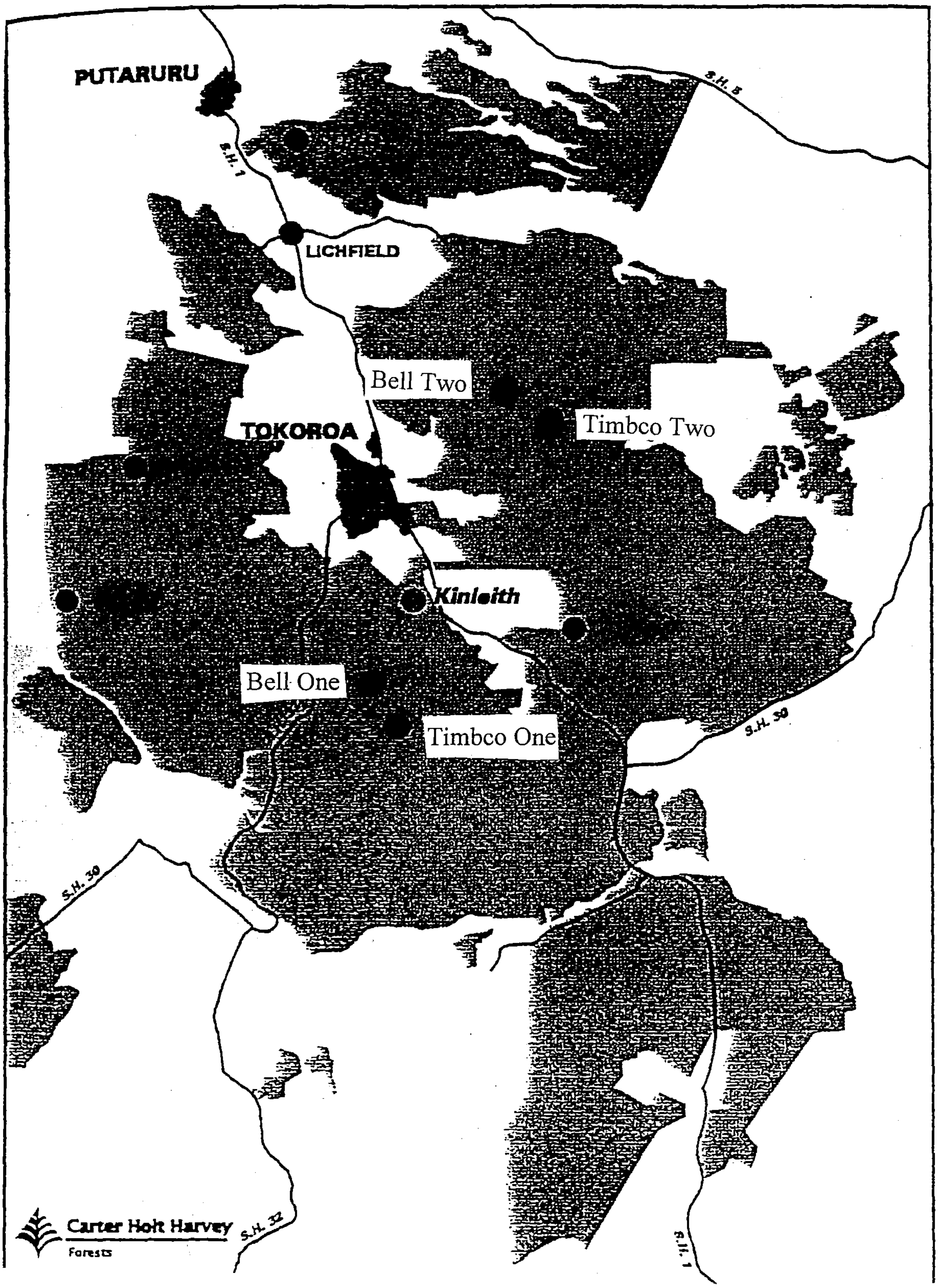
TABLE 3-1: STAND DETAILS[4].

Machine	SPH	Age (yrs)	Av. Ht. (metres)	Av. DBH (metres)	Piece Size ($metres^3$)	Tending History
Bell One[5]	~300	25	35.87	0.511	1.69	Thinned
Bell Two	~380	30	35.51	0.521	1.54	Pruned Thinned
Timbco One	~430	26	32.23	0.505	1.28	None
Timbco Two	~320	30	41.50	0.498	1.95	None

[4] Information obtained from CHHF databases.

[5] During this report reference will be to Bell One, Bell Two, Timbco One and Timbco Two. These will also be known as Operator One, Two, Three and Four respectively.

Figure 3-2: Stand Locations.



See Appendix I for detailed maps of the individual harvesting areas.

CHAPTER FOUR

MATERIALS AND METHODS

The required data for this study were collected over the period November 1995 to February 1996 from Carter Holt Harvey forests surrounding Tokoroa. It incorporated the following components:

4.1 SAMPLING STRATEGY

The most important piece of information was the relative break height and the diameter of the stem at the breakpoint. To calculate this, the total tree height, the height to the first break and the diameter at the breakpoint were required. Also recorded were wastage[6], diameter and length measurements of broken pieces above the first break to a diameter of ten centimetres. The sampling strategy was based around obtaining these variables. Section 4.5 details the sample size for each operator and machine.

4.2 HARVESTING AREA SELECTION

All the harvesting crews included in the study had an operator with at least four months continuous experience working the mechanical feller. Data were collected during normal operations. Ideally, the areas to be studied would have had similar age, piece size and ground condition dimensions. However due to operational circumstances at the time this was not possible.

[6] Wastage is defined as the piece of stem that would be removed to leave a flush end.

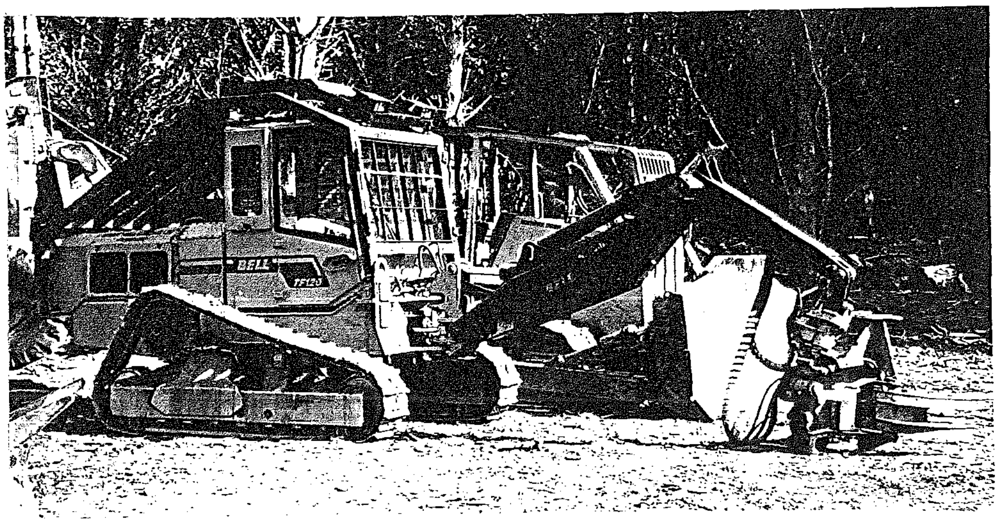
4.3 MECHANICAL HARVESTING EQUIPMENT

All four mechanical harvesting machines working in *Pinus radiata* in Kinleith forest were studied. Two of the machines were Bell TF120 feller-bunchers and the other two were Timbco T445 hydro bunchers. Each machines specifications are outlined below.

BELL TF120 FELLER BUNCHER[7]

The 10,100 kg TF120 is driven by a 4 BTA 3.9 Cummins engine, delivering 84kW (112hp) of power. It has a closed centre, load sensing hydraulic system. The booms 180° slew arc enables directional felling up to 4.1 metres without moving the carrier. The rotator-mounted feller-director head is comprised of a 3-arm grapple and chainsaw bar. The Bell TF120 has the ability to fell large trees using a two-cut method, similar to that used by motor-manual fallers. This makes determining a recommended tree size difficult because in theory very large trees could be felled, albeit with varying degrees of confidence.

Plate 4-1: Bell TF120[8].



[7] Information supplied by Bell Equipment (N.Z) Ltd.

[8] Photos provided by Bell Equipment (NZ) Ltd. or taken on site.

The Bell operators used two main felling techniques depending on the tree size. Most trees were felled with a single cut. In this case (see Plate 4-2 opposite) the operator positions the machine directly behind the tree, placing the felling head at the trunk base. The 3-arm grapple holds the base and the chainsaw bar is operated while the carrier places forward pressure on the tree.

Plate 4-2: Single Cut.

Plate 4-3: Initial Cut.

When trees are to large for a single cut, two-cut method is employed. Here an initial cut is made in the front half of the trunk (Plate 4-3 opposite) after which the operator continues as in the one-cut felling.

Plate 4-4: Tree Directing.

Trees are directed in the air as much as possible (Plate 4-4 opposite) and released before ground contact. This limits head stress and bunching time. While some bunching is possible during the felling process, the remainder is completed once the trees are on the ground.

TIMBCO T445 HYDRO BUNCHER[9]

The TIMBCO has a CAT 330 D7 undercarriage featuring a two speed drive capable of speeds up to 6km/h. This is powered by a 6CT 8.3 215hp standard Cummins engine. The cab sits on a self-leveling turntable, with a variable displacement and pressure compensated hydraulic system. The TIMBCO has a 28" bar saw with directional felling capabilities.

Plate 4-5: Timbco T445.

During the study only one felling method was observed, a single cut. As with the Bell, the Timbco is positioned behind the tree with felling head placed at the trunk base (see Plate 4-6 next page). The felling head grasps the tree and while the chainsaw operates, the boom places upward and forward pressure. The majority of the bunching is completed while felling (see Plate 4-7 next page) as the Timbco has limited ability in moving trees already on the ground.

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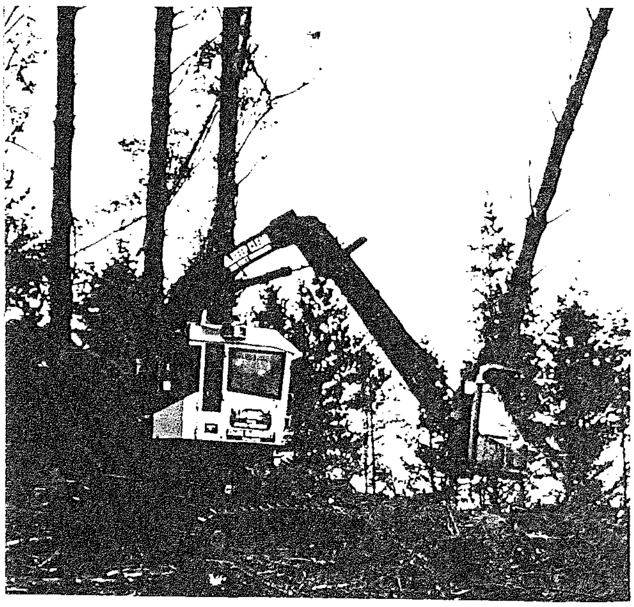
[9] Information supplied by Titan Plant Services (N.Z) Ltd.

Plate 4-6: Head Positioning.

Plate 4-7: Tree Directing.

Plate 4-8: Tree Bunching.



The Timbco is able to keep some trees vertically orientated even when completely severed from the ground (see Plate 4-8 opposite). This highlights its great stem control capabilities.

The degree of control for each machine appeared dependant on the tree size and the ground conditions. While both machine types had some degree of control, the Timbco had the greatest. In some cases, the operators were able to control the falling tree right up to the point of hitting the ground.

4.4 SAMPLING METHOD

The necessary data were collected from four different harvesting sites within Kinleith forest. Trees were selected from areas where the feller-bunchers would be working in the immediate future. As in other studies (Piebenga, 1989; Temple, 1995), selection was random, however trees that were malformed or multi-leadered were excluded from the study. All selected trees were individually numbered and their dbhob[10] recorded. A breast height band (at 1.40 metres above ground level on the uphill side of the tree) was painted to act as a reference point and to aid in tree location once felled.

In previous studies (Piebenga, 1989; Temple, 1995) tree height was attained after felling by piecing the broken tree back together and then measuring it. If all the pieces could not be recovered the tree was discarded from the study. This resulted in long periods spent searching for stem pieces and in some cases wasted effort if the tree was not reconstructed in full. To over come this problem, tree height was measured before felling using a hypsometer called a FORESTORS VERTEX™. The Vertex calculates the tree height by using two angles and one distance (See Appendix II for operational details). Three tree height measurements can be calculated to produce an average.

The trees were then left to be felled by the harvesting gang. Arrangements were made with the gangs so that the felled logs were not removed until the required measurements had been recorded.

Once felled, the distance to the first break on the stem from the 1.40 metre paint mark was measured and, where identifiable, the reason for the break. Also recorded was the slope of the felling zone measured from the log butt end to the crown using a Sunnto clinometer. In cases where trees were felled across a change in slope, two measurements were made. One from the log butt to the mid-point of the change and the second reading from the mid-point to the crown. At the first break and each subsequent break, the wastage, stem diameter and piece length were measured. All this data was recorded on a Husky Hunter portable computer. See Figure 4-2 for a visual guide to the measurements made.

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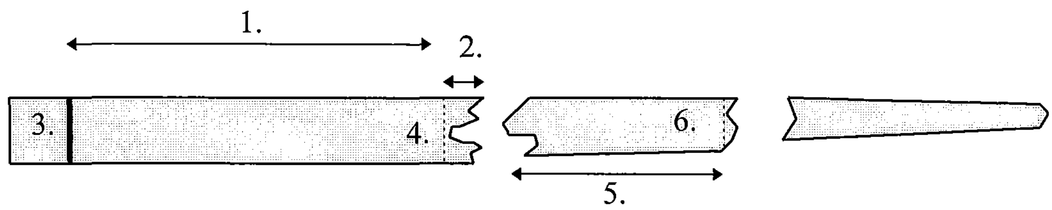
[10] dbhob - diameter at breast height over bark measured at 1.40m above the ground.

Figure 4-2: Pictorial View of Broken Stem.



1. Height to the first break, measured from the painted mark (3) to the start of the break (4) The length from the paint mark to the ground (1.40 metres) is added to give the height to the first break.
2. The wastage measurement. This is the piece of the stem that is lost when it is trimmed. This is measured from the start of the break to the end of the stem.
3. The painted mark placed at 1.40 metres above the ground.
4. The start of the first break. The break diameter is measured here.
5. The length of a stem piece above the first break. This is measured from the start of the stem piece to the start of the next break.
6. The start of the next break. The break diameter is measured here.

4.5 SAMPLING INTENSITY

The number of trees required for a sufficient sample depends on the variation within the population and the confidence level required. The following formula (Freese, 1967) is used to calculate the number of trees required to be sampled.

Equation 4-1:

$$n = \frac{s^2 t^2}{E^2}$$

where

where	n	=	sample size
	t	=	t-statistic
	s^2	=	estimate of the population variance
	E	=	precision required

To solve Equation One, an estimate of the population variance (s^2) was required. This was derived from a preliminary study where 45 trees were measured for their breakpoint. The sample variation obtained was used as an estimate of the population variation. It was decided that each machine would have a different population variance so the sample size for each machine was determined individually. These data are summarised in Table 4-2.

TABLE 4-2: SUMMARY OF THE ESTIMATE OF THE POPULATION VARIANCE AND SAMPLE SIZE.

Machine	s^2
Bell One	0.0183819
Bell Two	0.0140599
Timbco One	0.0275973
Timbco Two	0.0115432

See Appendix III for complete calculations.

Using the above figures, Equation 4-1 was solved to produce the required sample sizes. A precision of 0.05 metres at the 95% confidence level was adopted for this study.

TABLE 4-3: REQUIRED SAMPLE SIZE FOR INDIVIDUAL FELLING MACHINES.

Machine	Sample Size
Bell One	53.76 (54)
Bell Two	41.12 (41)
Timbco One	80.71 (81)
Timbco Two	33.75 (34)

See Appendix III for complete calculations.

As can be seen from Table 4-3, the required sample size for Bell Two and Timbco Two is less than the number already sampled during the preliminary study. For the purposes of this report the greater sample size will be used. This will have no negative effect on the results, it is in fact desirable to use as big a sample size as possible.

CHAPTER FIVE

RESULTS

5.1 GENERAL RESULTS

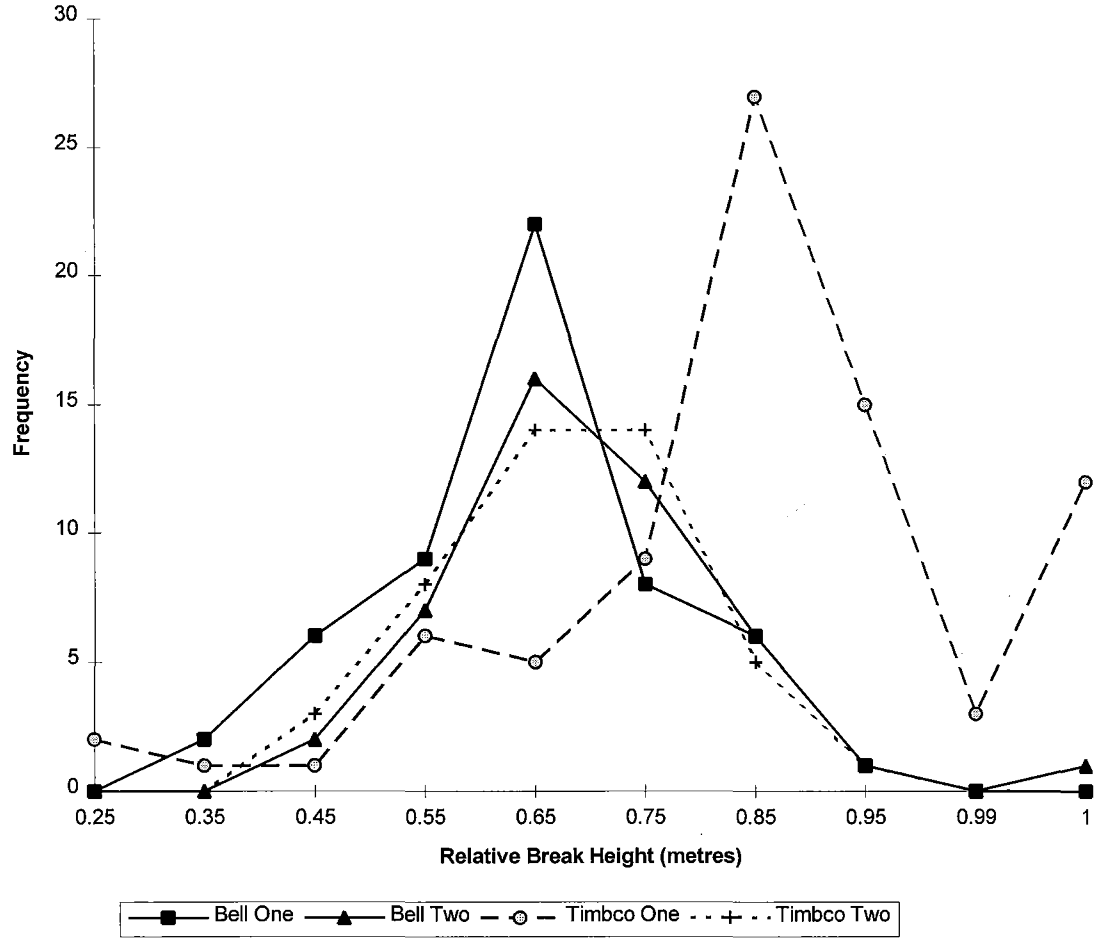
As can be seen in Table 5-1 below, two of the machines, Bell One and Timbco Two, broke all the trees they felled during the study. Bell Two and Timbco One however did not, breaking just less than 98% and 84% of their trees respectively.

Timbco One had the highest mean relative break height of 0.8646 but also had the greatest variability. Bell One had the lowest mean relative break height with 0.6913.

TABLE 5-1: MACHINE COMPARISONS.

	Bell One	Bell Two	Timbco One	Timbco Two
Breakage (%)	100	97.8	84.0	100
Rel. Break Height:				
- Mean	0.6913	0.7371	0.8646	0.7286
- Std. Dev.	0.1254	0.1186	0.1595	0.1074

Figure 5-1: Relative Break Height Frequencies.



As can be seen in Figure 5-1 above, the relative break heights of Bell One, Two and Timbco Four are fairly normal distributed about their means. Timbco One however is heavily skewed to the right with the majority of its break heights being greater than 85%.

One of the objectives of this study was to determine what factors of the landing environment affect stem breakage. Previous studies have shown this to be an important variable (NZFP report, 1977; Manley, 1977; Murphy, 1984; Piebenga, 1989). Table 5-2 below shows the reasons for log breakage during felling. As can be seen, the majority of the breakage (66.6%) could not be explained. From what could be, falling trees hitting already felled logs accounted for the majority of the breakage (6.6% of the total breakage or nearly half of the "explained" breakage). This was closely followed by breakage due to falling trees striking stumps.

TABLE 5-2: REASON FOR BREAKAGE.

	Bell One	Bell Two	Timbco One	Timbco Two	Total
Hit Log*	9	5	15	5	34
Hit Stump+	4	1	10	5	20
Slope Change	3	2	4	1	10
Ground Undulation	2	0	1	1	4
Other♣	2	2	2	1	7
Unknown	34	35	49	32	150

*Logs felled recently, excludes old native logs.

+Stumps of recently felled *Pinus radiata.*

♣Other includes breakage due to whiplash and breakage in mid-air.

CHAPTER SIX

DATA ANALYSIS

6.1 RELATIVE BREAK HEIGHT AND VARIATION

As there were four different machine operators, it was decided to investigate if each operator could be regarded as the same in terms of relative break height. It was also decided to determine if the two feller-buncher machine types could be considered the same.

Usually an analysis of variance using the general linear model (GLM) procedure in the Statistical Analysis System (SAS) would be used to test this. However two important assumptions, that of data normality (see Figure 5-1) and equal sample variances, could not be satisfied. Various data transformations such as square root, arc sine and arc sine square root were attempted to remedy this, however they were unsuccessfully Instead the Kruskal-Wallis test, a non-parametric alternative (one that does not assume a normal distribution) to the usual analysis of variance was used (Montgomery, 1976).

See Appendix IV for full details of SAS outputs for the following hypotheses.

The first hypothesis is used to determine if there is any significant difference between operators.

Hypothesis One: There is no significant difference between operators.

$$H_0: \quad \mu_{\text{OPERATOR 1}} = \mu_{\text{OPERATOR 2}} = \mu_{\text{OPERATOR 3}} = \mu_{\text{OPERATOR 4}}$$

TABLE 6-1: SUMMARY OF KRUSKAL-WALLIS TEST ONE.

CHISQ = 62.154	DF = 3	P-value = 0.0001

The results indicate that the H_0: should be rejected at the 0.01 level of significance. There is a significant difference between operators.

The next hypothesis tests to see if there is any significant difference between operators of the Bell TF120 feller-buncher.

Hypothesis Two: There is no significant difference between the two operators.

$$H_0: \quad \mu_{\text{OPERATOR 1}} = \mu_{\text{OPERATOR 2}}$$

TABLE 6-2: SUMMARY OF KRUSKAL-WALLIS TEST TWO.

CHISQ = 3.2363	DF = 1	P-value = 0.0720

The results show that the H_0: can be accepted at the 5% level.

The third hypothesis investigates if there is any significant difference between Timbco 445 operators.

Hypothesis Three: There is no significant difference between operators.

$$H_0: \quad \mu_{\text{OPERATOR 3}} = \mu_{\text{OPERATOR 4}}$$

TABLE 6-3: SUMMARY OF KRUSKAL-WALLIS TEST THREE.

CHISQ = 33.225	DF = 1	P-value = 0.0001

The test indicated that at the 0.01 level the H_0: should be rejected. There is a very significant difference between Timbco operators.

As hypothesis one showed there is a significant difference between operators, the following hypotheses 4 to 7 are used to determine which operators, if any, could be considered to be the same.

Hypothesis Four: H_0: $\mu_{\text{OPERATOR 1}} = \mu_{\text{OPERATOR 3}}$

Hypothesis Five: H_0: $\mu_{\text{OPERATOR 1}} = \mu_{\text{OPERATOR 4}}$

Hypothesis Six: H_0: $\mu_{\text{OPERATOR 2}} = \mu_{\text{OPERATOR 3}}$

Hypothesis Seven: H_0: $\mu_{\text{OPERATOR 2}} = \mu_{\text{OPERATOR 4}}$

TABLE 6-4: SUMMARY OF KRUSKAL-WALLIS TESTS FOUR.

H_0:	CHISQ	DF	P-value
4	42.773	1	0.0001
5	2.5	1	0.1138
6	27.834	1	0.0001
7	0.01565	1	0.9005

The results of the tests indicate that operators one, two and four are not significantly different while operator three is significantly different from all the other operators at the 5% level.

The final hypothesis is to determine if there is a significant difference between the Bell TF120 and Timbco T445 machines.

Hypothesis Eight: There is no significant difference between machine types.

$$H_0: \quad \mu_{\text{Bell TF120}} = \mu_{\text{Timbco T445}}$$

TABLE 6-5: SUMMARY OF THE KRUSKAL-WALLIS TEST FIVE.

CHISQ = 31.050	DF = 1	P-value = 0.0001

The results show that we can confidently reject the H_0: at the 0.01 level. There is a significant difference between the machines.

6.2 NESTED GENERAL LINEAR MODEL (GLM)

Nested analysis of variance can be used to determine the magnitude of the variance attributable to various levels of variation in a study (Sokal & Rohlf, 1981). Despite the results of the Kruskal-Wallis tests, namely the significant difference between machine types and between some operators, the breakage information was pooled together to create a larger data set for the study. The relative break height variance was subdivided into that among machines and that among operators within one machine. For a two level nested random effects analysis of variance, the equation becomes:

Equation 6-1: $$Y_{ijk} = \mu + A_i + B_{ij} + E_{ijk}$$

where

Y_{ijk}	=	the *k*th relative break height in the *j*th operator of the *i*th machine.
μ	=	the parametric mean of the population.
A_i	=	the random contribution of the *i*th machine.
B_{ij}	=	the random contribution of the *j*th operator of the *i*th machine.
E_{ijk}	=	the error term of the *k*th relative break height of the *j*th operator of the *i*th machine.

The variances were calculated using the NEST procedure in SAS. The results are summarised in Table 6-6 below. See Appendix V for full details of the SAS output.

TABLE 6-6: SUMMARY OF NESTED EFFECTS ANALYSIS OF VARIANCE FOR RELATIVE BREAK HEIGHT.

Variance Source	Variance Component	Percent of Total
Machine	0.002545	9.8740
Operator	0.005151	19.9826
Error	0.018080	70.1435
Total	0.025776	100.0000

6.3 PREDICTIVE BREAKAGE MODEL

One objective of this study was to develop a model that could accurately predict the breakheight of an individual tree given tree, stand and machine information. In an attempt to achieve this, modelling was completed using the GLM procedure in SAS. Break point variables, relative break height (RELBRK), breakheight (BRKHT) and diameter at the point of break (DIA), were modelled against height (HEIGHT), dbhob (DBH), change in slope (CSLOPE) and machine type (DUM). The DUM variable was set as "1" for the Bell TF120 and "0" for the Timbco T445. Operator variables were not included as this would create very specific models. Factors that affect an operators contribution to breakage can be unique to an operator while those common to all can express themselves in varying degrees. This makes devising a model that incorporates operator variables very difficult and creates one which is subject to change. Table 6.7 below shows the results attained for each. See Appendix VI for full details of the SAS output.

TABLE 6.7: SUMMARY OF GLM ONE.

	RELBRK	BRKHT	DIA
DBH, CSLOPE, HEIGHT & DUM Variables	$R^2 = 0.2508$	$R^2 = 0.1881$	$R^2 = 0.3277$
	F = 18.41	F = 12.75	F = 26.81
	Pr > F 0.0001	Pr > F 0.0001	Pr > F 0.0001

DIA as the independent variable produced the highest R^2 of 0.3277. RELBRK and BRKHT produced R^2 of 0.2508 and 0.1881 respectively.

The SAS output showed that DBH and CSLOPE variables did not contribute significantly to the RELBRK and BRKHT models. CSLOPE was the only variable not significant in the DIA model. For model simplicity, these were excluded and the GLM run again. These results are shown in Table 6.8 below. As can be seen, the R^2 have not altered significantly. See Appendix VII for full details of the SAS output.

TABLE 6.8: SUMMARY OF GLM TWO.

	RELBRK	BRKHT	DIA
HEIGHT & DUM Variables {also DBH for DIA}	$R^2 = 0.2499$	$R^2 = 0.1877$	$R^2 = 0.3277$
	F = 36.98	F = 25.65	F = 35.90
	Pr > F 0.0001	Pr > F 0.0001	Pr > F 0.0001

DIA and RELBRK models had the greatest R^2 values with 0.3277 and 0.2499 respectively. Both these models produced statistically significant equations, as shown below.

DIA Equation One:

$$Y = \underset{(17.33)}{-0.26994} + \underset{(-6.31)}{-0.00886} \times X_1 + \underset{(-5.72)}{0.05543} \times X_2 + \underset{(3.05)}{0.18414} \times X_3$$

where:

Y = Diameter at the Point of Break (metres)

X_1 = Tree Height (metres)

X_2 = DUM (machine) {Bell TF120 = 1, Timbco T445 = 0)

X_3 = Tree Diameter at Breast Height (metres)

t-values are given in parenthesis.

Summary statistics relating to the DIA equation can be seen in Appendix VII.

RELBRK Equation One:

$$Y = \underset{(17.33)}{1.27333} + \underset{(-6.31)}{-0.01287} \times X_1 + \underset{(-5.72)}{-0.10171} \times X_2$$

where:

Y = Relative Break Height

X_1 = Tree Height (metres)

X_2 = DUM (machine) {Bell TF120 = 1, Timbco T445 = 0}

t-values are given in parenthesis.

Summary statistics relating to the RELBRK equation can be seen in Appendix VII.

Due to the low R^2 values, it was decided that the data points for which the reason for breakage was known, such as hitting logs or stumps, be removed. This would allow an equation to be produced to model breakage due to machine type, tree measurements and change in slope variables only. This reduced the data set from 225 observations to 154. Table 6.9 below highlights the GLM results for the altered data set. See Appendix VIII for full details of the SAS output.

TABLE 6.9: SUMMARY OF GLM THREE.

	RELBRK	BRKHT	DIA
DBH, CSLOPE, HEIGHT & DUM Variables	$R^2 = 0.4897$	$R^2 = 0.3365$	$R^2 = 0.5483$
	F = 35.75	F = 18.90	F = 45.21
	Pr > F 0.0001	Pr > F 0.0001	Pr > F 0.0001

Removing the "explainable" data greatly improved the R^2 for all the models although they are still low. Again DIA produced the highest R^2 value with 0.5483.

DBH and CSLOPE variables were not significant and were thus removed to simplify the models. Table 6.10 below shows these results. See Appendix IX for full details of the SAS output.

TABLE 6.10: SUMMARY OF GLM FOUR.

	RELBRK	BRKHT	DIA
HEIGHT & DUM Variables	$R^2 = 0.4776$	$R^2 = 0.3204$	$R^2 = 0.5410$
	F = 69.03	F = 35.59	F = 88.97
	Pr > F 0.0001	Pr > F 0.0001	Pr > F 0.0001

This final GLM run returned the best R^2 values. DIA and RELBRK models had the greatest values with 0.5410 and 0.4776 respectively. Both these models produced statistically significant equations.

DIA Equation Two:

$$Y = -0.33018 + 0.01247 \times X_1 + 0.07513 \times X_2$$
$$\qquad (-8.34) \qquad (11.37) \qquad (7.59)$$

where:

Y = Diameter at the Point of Break (metres)

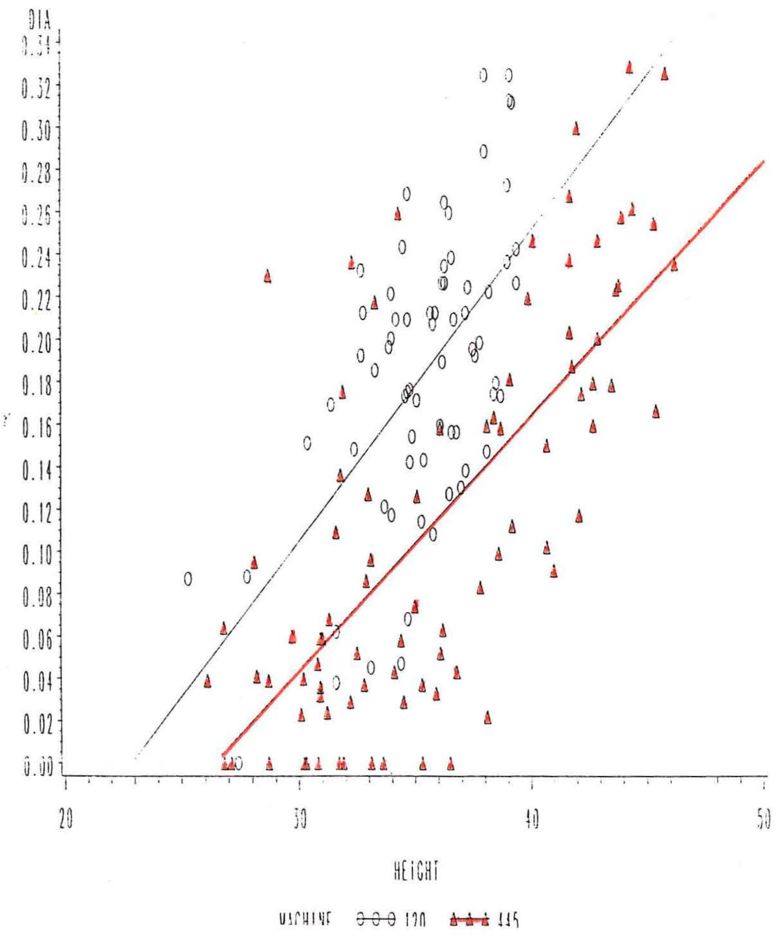
X_1 = Height (metres)

X_2 = DUM (machine) {Bell TF120 = 1, Timbco T445 = 0}

t-values are given in parenthesis.

Summary statistics relating to the DIA equation can be seen in Appendix X. The absence of bias is highlighted by the random scattering of residuals versus predicted values as shown in Figure I in Appendix X. Figure 6-1 below shows how well the model estimates the actual data.

Figure 6-1: Diameter at the Breakpoint Versus Height by Machine Type.



RELBRK Equation Two:

$$Y \quad = \quad \underset{(21.98)}{1.42903} \; - \; \underset{(-9.00)}{0.01608} \times X_1 \; \underset{(-8.04)}{-0.12952} \times X_2$$

where:

Y = Relative Break Height

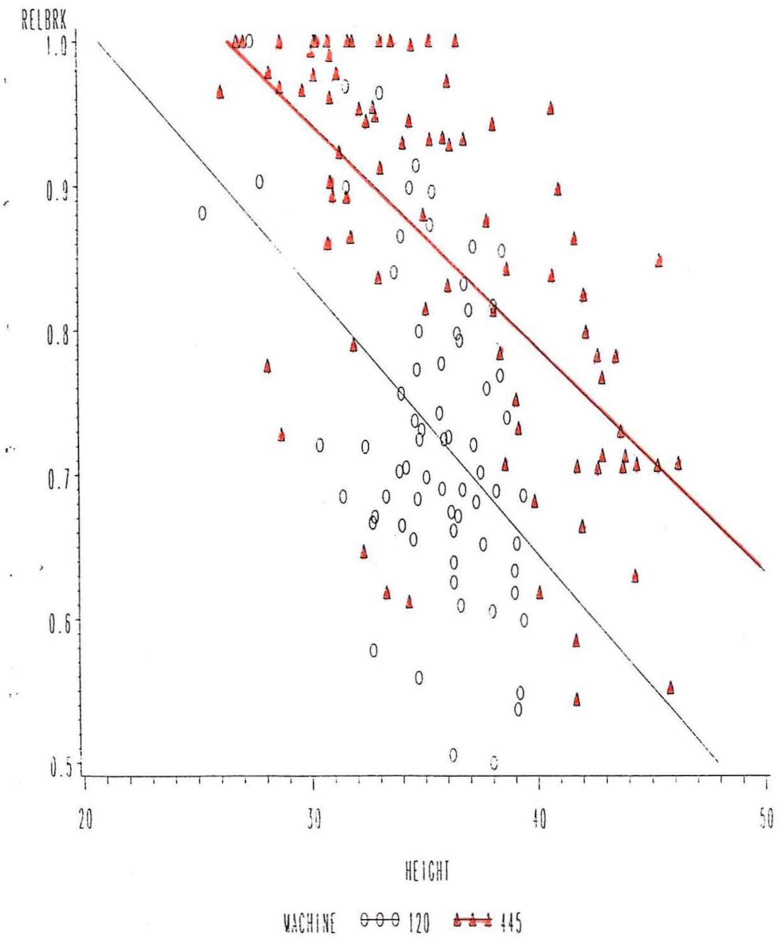
X_1 = Height (metres)

X_2 = DUM (machine) {Bell TF120 = 1, Timbco T445 = 0}

t-values are given in parenthesis.

Summary statistics relating to the RELBRK equation can be seen in Appendix X. The absence of bias is highlighted by the random scattering of residuals versus predicted values as shown in Figure II in Appendix X. Figure 6-2 below shows how well the model estimates the actual data.

Figure 6-2: Relative Breakheight Versus Height By Machine Type.



CHAPTER SEVEN

DISCUSSION

7.1 GENERAL DISCUSSION OF RESULTS

7.1.1 Reasons for Breakage

With so much of the breakage being unexplained it leaves the question of why a tree breaks. Here I must reiterate the observation made by Twaddle (1987) that other reasons for breakage, yet to be understood, relate to the physical structure of trees and the dynamics involved when a tree strikes the ground. Further research in to these phenomena is required.

From the breakage that could be adequately explained, it is not surprising that a high percentage of it results from trees hitting previously felled logs. Feller-bunchers have some ability to hold severed trees vertical and move them in to better dropping positions. As the name implies, the machines allow operators to bunch logs in groups, which increases skidder production, but also increases the chance of breakage. Trees are more likely to break if they fall cross another or if hit across-widths. These trees often broke at the point of impact. Ones laid out parallel to one another broke closer to their tops, if at all.

High breakage due to trees striking stumps is also not surprising. Unlike logs, stumps are not a moveable hazard and are ever present. However once a few trees have been bunched, the likelihood of hitting stumps is reduced as they become covered.

The incidence of breakage as a result of hitting felled logs is dependant on the extent an operator is bunching and the operators' skill level. However the incidence of breakage due to hitting stumps is also a function of stocking levels (higher levels produce more stumps).

Breakage due to slope changes and ground undulation were less common, but still an important source. In some instances, operators had no choice when dropping trees across changes in slope. In other cases, preventative action was possible but not always taken.

The identification of some of the factors that cause breakage has implications for forest managers looking for means of reducing felling breakage. Harvesting machine operators need to be made aware of these factors and possible techniques of mitigating them. With around 35% of the total breakage being due to known factors, such as logs, stumps and changes in slope, some of this may have been avoided, or at least reduced, if operators had been conscious of their effects. Operator education is the key.

7.1.2 Relative Break Height and Variation

The numerous Kruskal-Wallis tests indicated that not all the operators could be regarded as the same. Operator Three has a much greater relative break height than the other operators which explains the significant difference test result. There appears to be no apparent explanation for this. There are no obvious features in either the stand dimension information or the amount of operator experience that would help explain the greater relative break height. Operator Three worked in the most difficult harvesting area encountered during the study but had the highest relative break height. It had the greatest average slope, the greatest average change in slope, more broken ground and very heavy undergrowth with vines and climbing vegetation. All these factors greatly increase the difficulties of felling. It is also perhaps possible that more care was taken by the operator because of this.

While the test results showed Operators One, Two and Four were not significantly different, they also highlight the fact that Operators Two and Four were more similar to one another than to Operator One.

Again the reasons for this are hard to determine. While the operators all had different amounts of operating experience, they all had at least four months operating their respective machines. It is generally accepted that a steep learning curve is experienced during the first three months of operation[11]. After this time, increases in skill level occur less rapidly. Based on this it could be expected that all the operators had a similar level of skill and therefore does not help explain any similarities or differences. Some of the difference could be due to different machinery but the similarity between Operators Two and Four severely weakens this argument. Probably the biggest influencing factor is the differences between stands, namely the landing zones. Both Operators Two and Four worked in gently sloping areas where ground undulations and undergrowth vegetation was light. In contrast Operator Three, and to lesser extent Operator One, worked in areas where heavy undergrowth, slope change and ground undulation was the norm. The generally "rougher" ground conditions greatly affects the operators ability to manoeuvre their machines during felling. This is supported by the fact that both these operators has the greatest variation in their relative break heights.

Testing also showed that there is a significant difference between machine types. This result is largely due to Operator Three being so very different from the other operators. While both machines have different felling techniques and abilities, whether there is actually a difference is a moot point.

[11] Personal Communication with mechanical harvester owners and operators.

7.1.3 Mechanical Breakage Functions

The following are the breakage functions derived for each of the operators. See Appendix X for details of the calculations.

Operator One (Bell One): Relative break height = 0.6913 +/- 0.0462 at the 95% confidence interval.

Operator Two (Bell Two): Relative break height = 0.7371 +/- 0.0478 at the 95% confidence interval.

Operator Three (Timbco One): Relative break height = 0.8648 +/- 0.0479 at the 95% confidence interval.

Operator Four (Timbco Two): Relative break height = 0.7286 +/- 0.0433 at the 95% confidence interval.

As the data analysis showed Operator One and Two, both Bell operators, were not significantly different from one another. Therefore the following breakage function applies to the Bell TF120 feller buncher.

Bell TF120 Relative break height = 0.7142 +/- 0.0470 at the 95% confidence interval.

The analysis also showed that Operator Three and Four, both Timbco operators, were significantly different from each other and could not be considered to be the same. However, despite the differences it is necessary to produce a breakage function that can be used for the Timbco T445 hydro-buncher.

Timbco T445 Relative break height = 0.7967 +/- 0.0456 at the 95% confidence interval.

7.1.4 Mechanised and Manual Breakage Functions

In 1989, Ian Piebenga derived a breakage function of 0.68 of the total height for 20-28 year old *Pinus radiata*. This function is the currently used by CHHF (Kinleith) in their MARVL operations. This study has produced breakage functions for four separate machines all of which have been greater than that determined by Piebenga. This indicates that there is indeed a difference in mean relative break heights between mechanical and manual felling techniques. An end result of this is that a separate breakage function is required for mechanical harvesting. Despite the differences between machine types they have been combined to produce the following function.

Mechanical breakage function: Relative break height = 0.7967 +/- 0.0463 at the 95% confidence interval.

7.1.5 Nested GLM

When dealing with factors nested within other factors, the variability associated with a nested factor is included within the total variation found in a factor classified in an upper tier. Thus determination of components of variance is especially useful for nested classification as this enables the estimation of the contribution of each separate factor to the total variability (Haywood, 1995).

The contribution to total variation from differences in machines was 9.87 %. The contribution to total variance due to differences among operators was 19.98 %. The majority of the total variance (70.14 %) was attributed to error - the differences between relative break heights of individual trees.

With almost 20% of the total variance being attributed to differences between operators, it highlights the effect individual operators have on breakage. Factors that affect an operators' performance such as motivation and skill level can all be improved by various means. An individual's motivation to work and on actual performance is influenced by the presence and nature of goals they are working towards. Given two people of equal ability, the one who sets specific and moderately difficult goals will work longer and achieve more than one who sets vague, easy goals or none at all (Smither, 1988). Once a goal or objective is specified, continued motivation depends in part on getting performance feedback. Working conditions and work motivation can be improved by creating cohesive, independent work teams. All jobs have a social aspect to them and this should not be ignored. Motivation is also affected by the opportunities to achieve. In situations were there is no chance to succeed or prospects for promotion, workers lack motivation. Skill levels can be improved good work planning, clear performance standards and individual crew member accountability.

7.1.6 Predictive Breakage Model

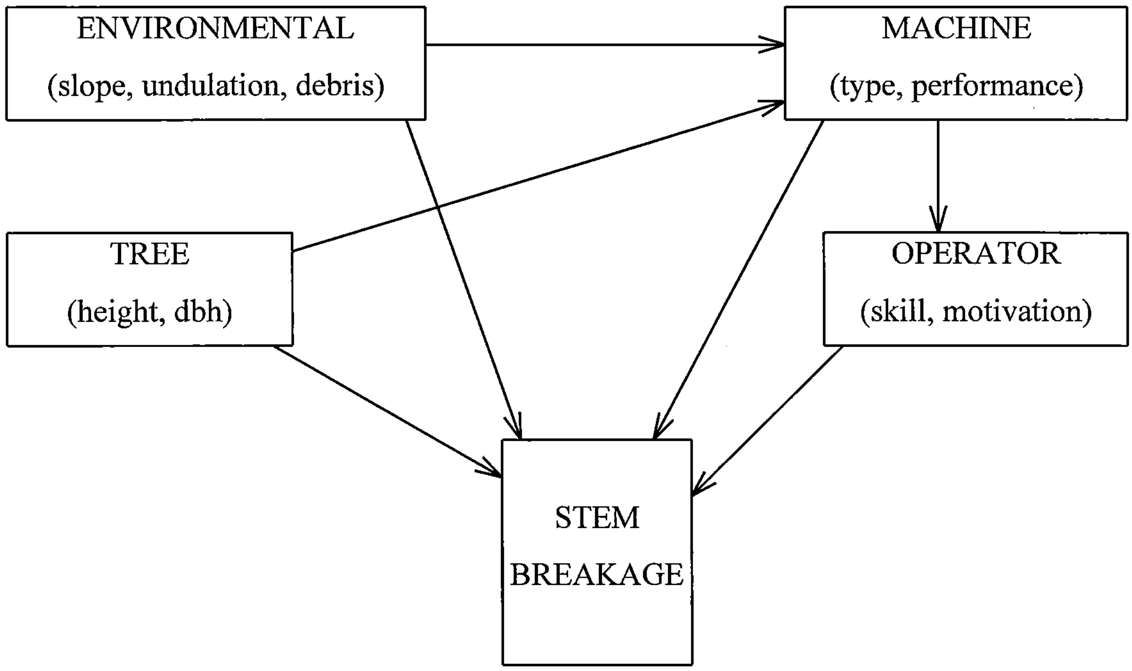
The relationship between mechanised break point variables and tree height, dbh, change in slope and machine type was examined. Two sets of equations were derived. The first from the complete data set, the second, from an altered set where the data points that arose due to explainable breakage, ie. hitting stumps or logs, were removed. While all the above tree, environment and machine variables contribute in some way to felling breakage, only some of them were found to be significant in the equations produced. For the first DIA equation, tree dbh and height plus machine type were significant, while only height and machine were in the first RELBRK model. In the second DIA and RELBRK equations, tree height and machine type were the only variables found to be significant.

Removing the explainable breakage data points improved the models accuracy. However a large proportion (~50%) of the variation is still left unexplained by both models. Operator effects, if included, account for some of this remainder but still a sizeable amount remains. To properly explain all the breakage variation a more complete model is required, particularly one that places increased emphasis on the landing environment. While all the equations had low R^2 values (an indication of an equations goodness of fit), this is not out of line with other research results (Piebenga, 1989).

Although the equations with the removed data points provide models with greater R^2 values, and hence are more accurate, the equations derived from the full data set are more useful for forestry managers. This is because although the effects of logs , stumps and other landing zone factors have been identified, it is very difficult for management to gauge their magnitude when utilising a breakage function. The complete data set equations allow breakage to be modelled in a "real" forest situation.

Mechanised felling breakage is a function of tree, environmental, machine and operator variables. The diagram below illustrates possible relationships between these various variables.

Figure 7-1: Relationships Between Factors Affecting Breakage.



Some of these factors have a two-fold effect on stem breakage. While they all have a direct impact on breakage, some factors have an secondary affect via other factors. Tree and environmental factors have an effect on the machine component which in turn influences the operator factors.

7.2 LIMITATIONS OF MODELS

The models produced can only be used to predict the diameter at the break point or the relative break point for trees of a similar dimension and felled with equivalent machinery as in this study. The second set of equations are also only applicable for trees that break for reasons other than striking logs or stumps or ground undulations.

All the DIA and RELBRK models have y-intercepts. This means that when the model variable height is zero, the models produce either diameter at break point or relative break height values for non-existent trees. This will not be a problem as long as the model is only used for the range of values in the original data set.

7.3 FUTURE RESEARCH

Future research into felling breakage, be it mechanical or manual, needs to move away from traditional tree measurements and concentrate more on the landing zone or environmental variables. These include slope length measurements and ground undulation and debris estimates. As these are hard variables to quantify and can be quite subjective, it is necessary for a universal system to be developed that can be used to survey ground conditions and characteristics in any area.

Operator effects are also an important area that requires further research. Factors such as motivation and skill level all influence an operators performance and need to be incorporated into future models. Although these are difficult to quantify they must be included to gain a fuller appreciation of the variables that affect breakage.

CHAPTER EIGHT

CONCLUSIONS

This project has reported on mechanical felling breakage from four harvesting machines working in Kinleith forest, central North Island, New Zealand. Two of the machines were Bell TF120 feller-bunchers , the others Timbco T445 hydro-bunchers.

The incidence of stem breakage ranged from 84% to 100%. Almost three-quarters of the breakage could not be explained. From the percentage that could, falling logs hitting other logs and stumps were the most common reason for breakage.

From the numerous Kruskal-Wallis tests performed, it was found that not all the machine operators could be considered to be the same. The two Bell operators were not significantly different while the Timbco operators were. It was also found that the two machine types were significantly different. On the basis of these results, separate breakage functions were derived for each machine.

The breakage function currently used by CHHF Kinleith, produced from manual felling data, was compared with the mechanical breakage functions and found to be different. Due to this, a combined mechanical breakage function was developed.

The variation of the relative break heights was investigated using a nested GLM and was shown to be mainly due to differences in individual tree breakheights not differences in machines or in operators.

The relationship between the break point variables, diameter at the point of break and relative break height and dbh, height, change in slope and machine type was investigated. Two sets of statistically significant equations were developed. None of the equations are complete models, at best they provide a partial explanation for mechanical breakage. Future research needs to focus on the landing zone and operator variables and how they influence felling breakage.

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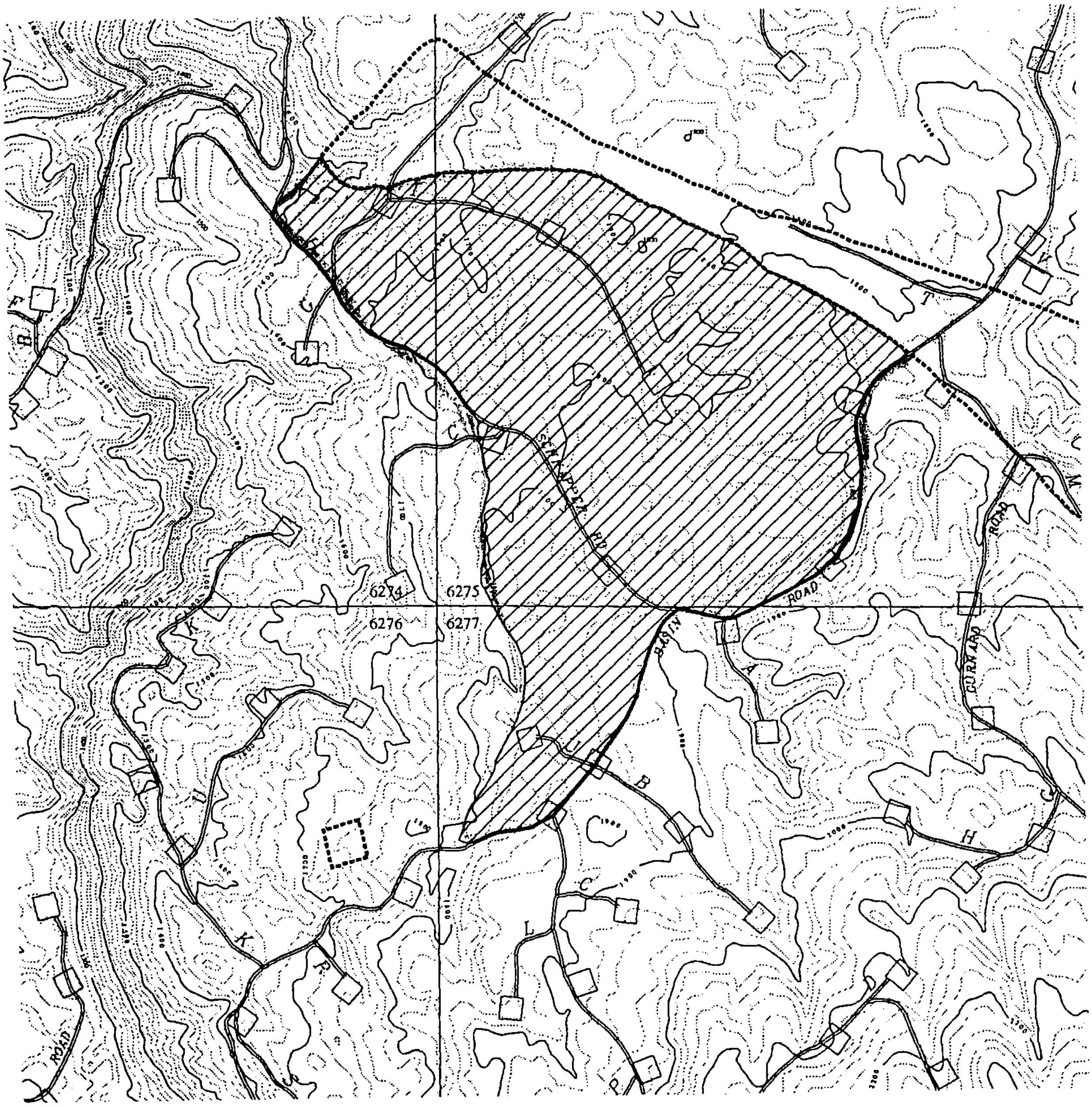
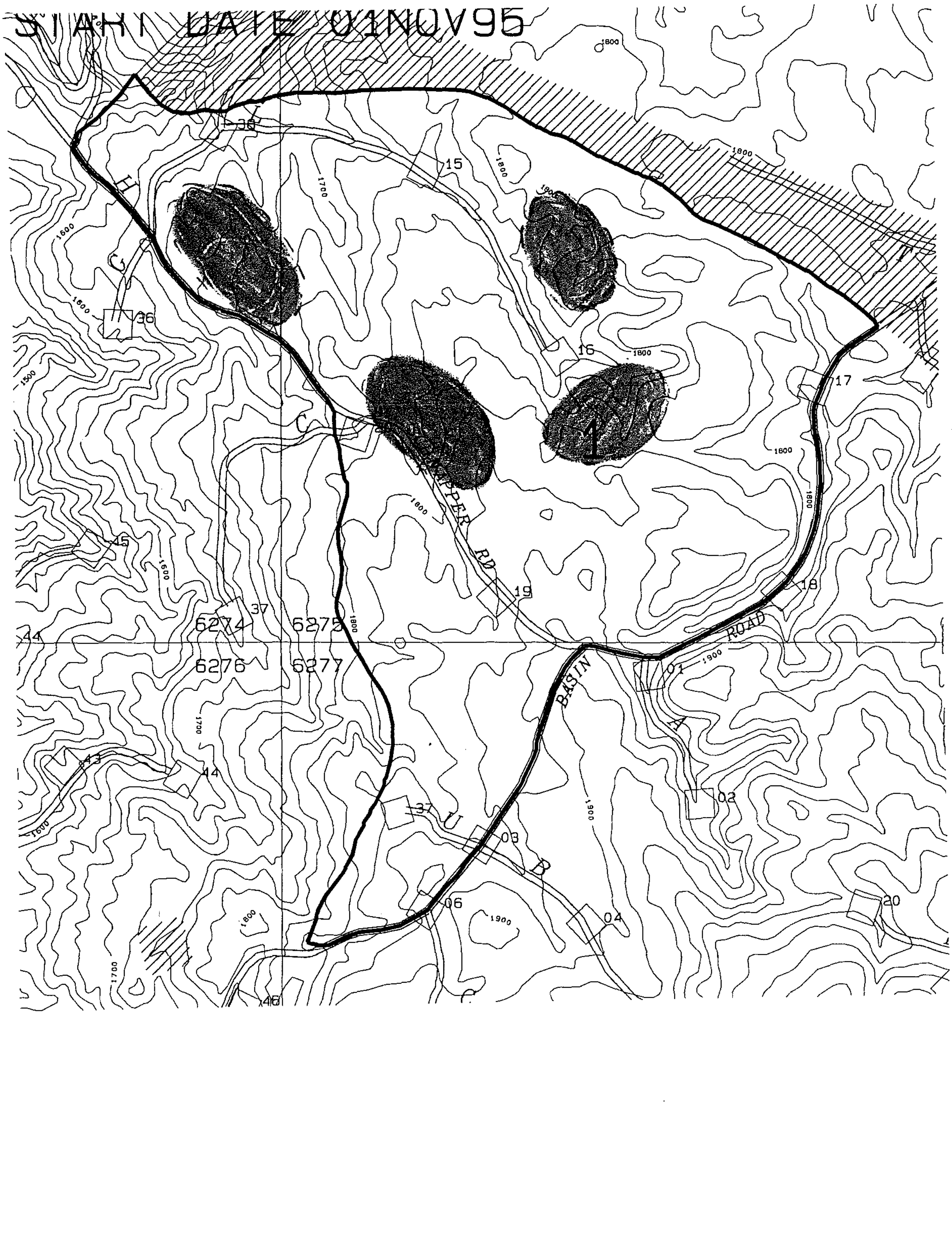
APPENDIX I

Map One: Bell One (Operator One) Harvesting Area Location

OP_ID: 27087

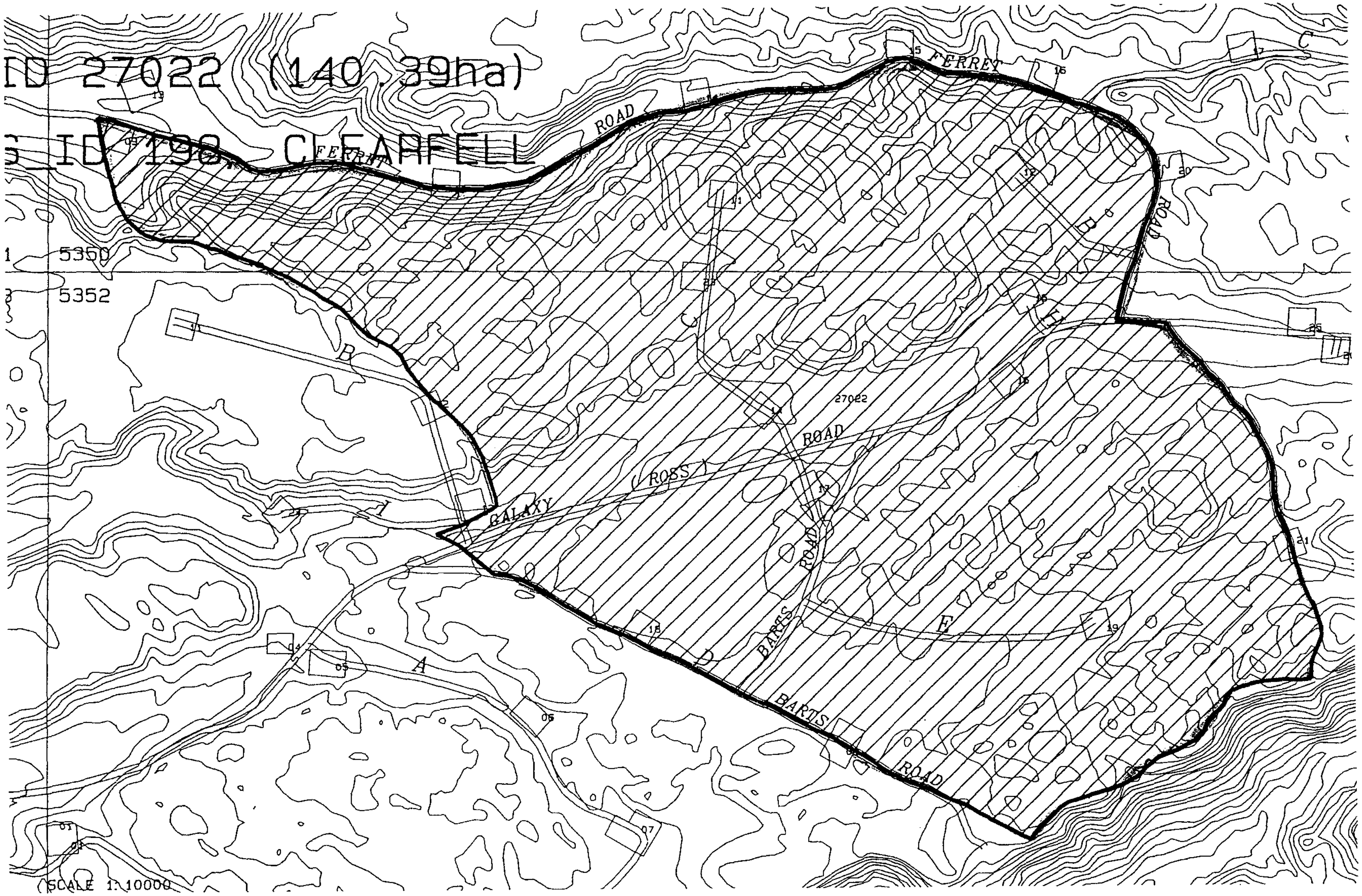


Map Two: Sampling Area Location

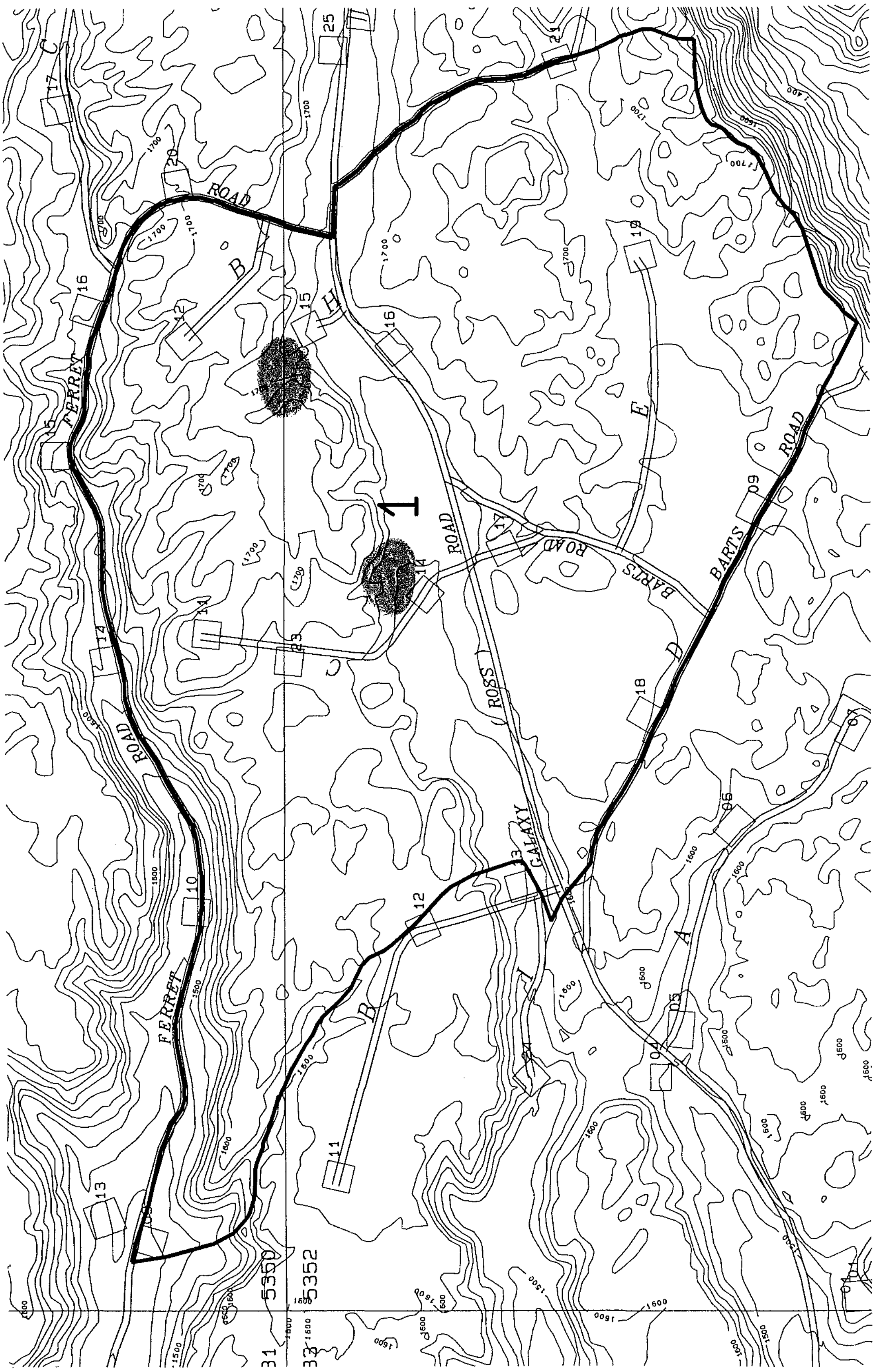


Map Three: Bell Two (Operator Two) Harvesting Area Location

OP_ID: 27022

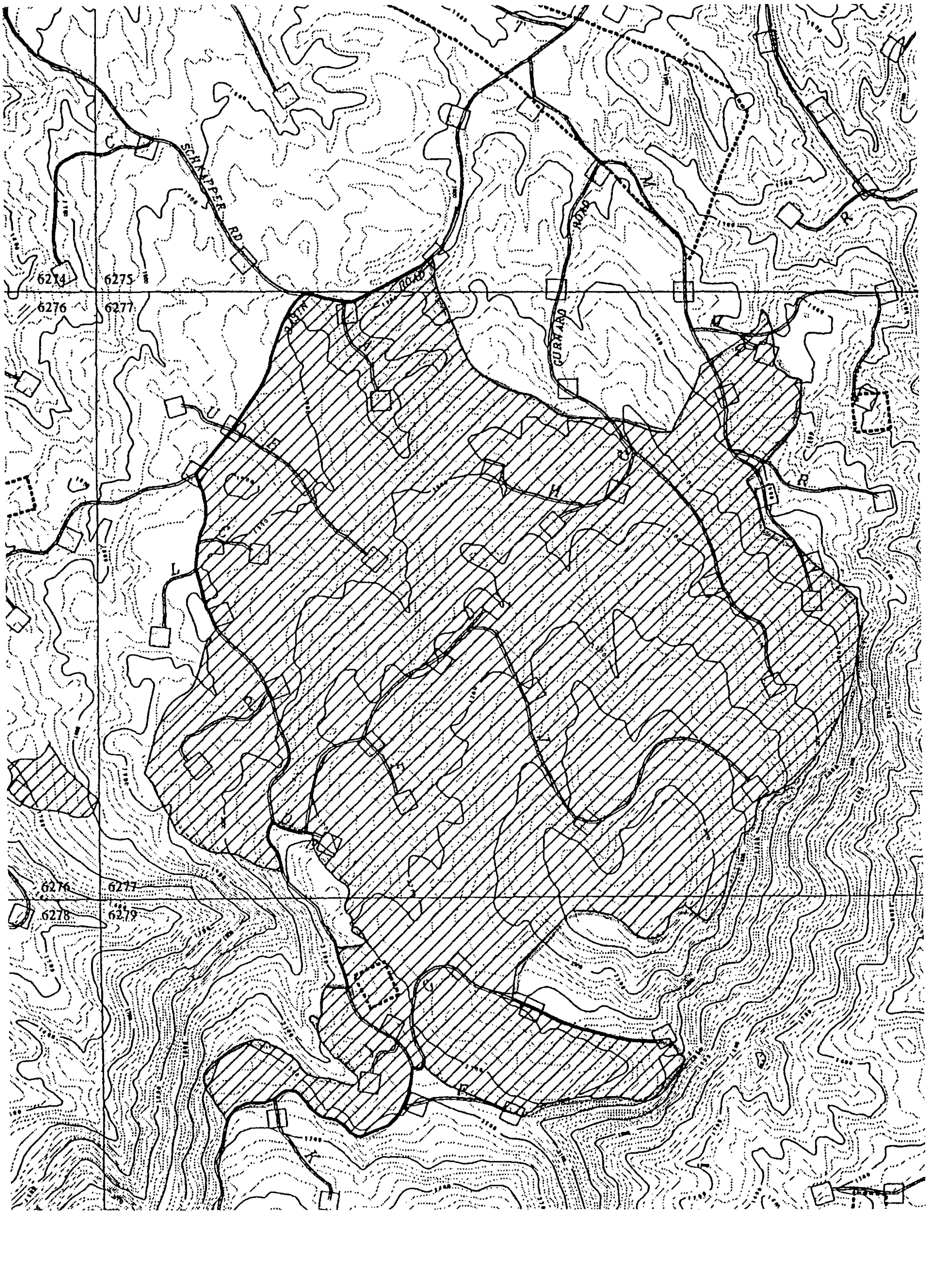


Map Four: Sampling Area Location

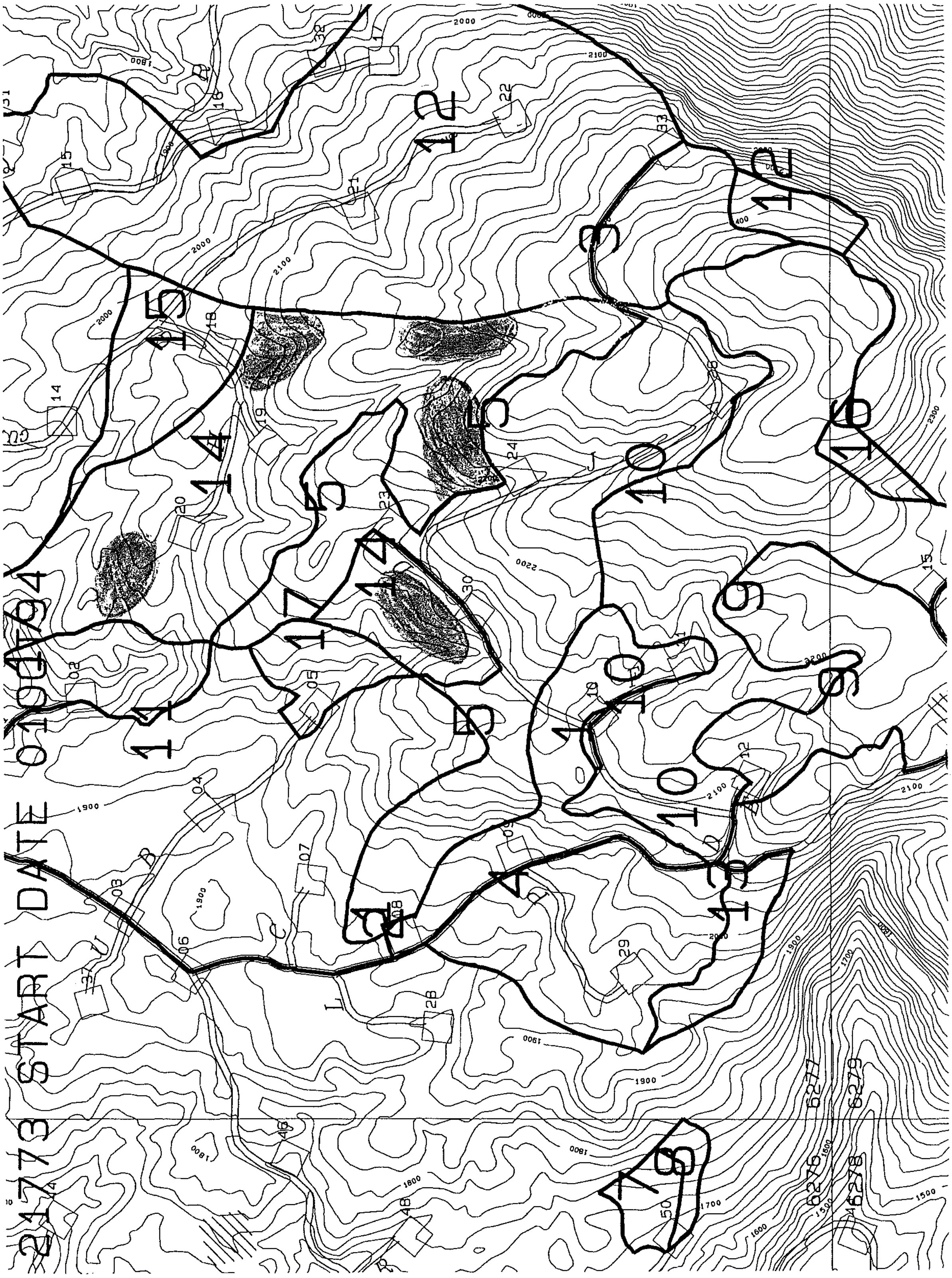


Map Five: Timbco One (Operator Three) Harvesting Area Location

OP_ID: 21773

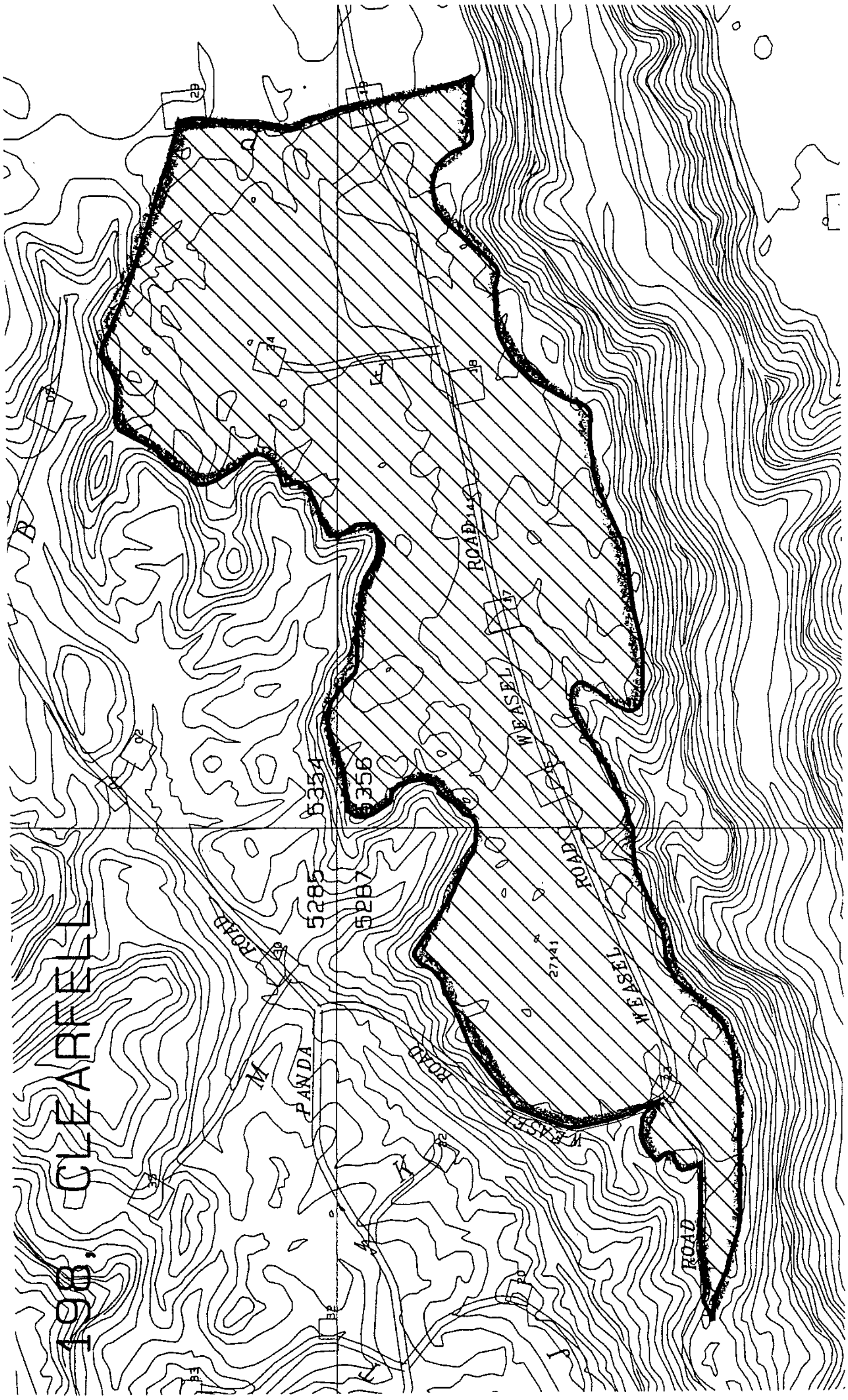


Map Six: Sampling Area Location

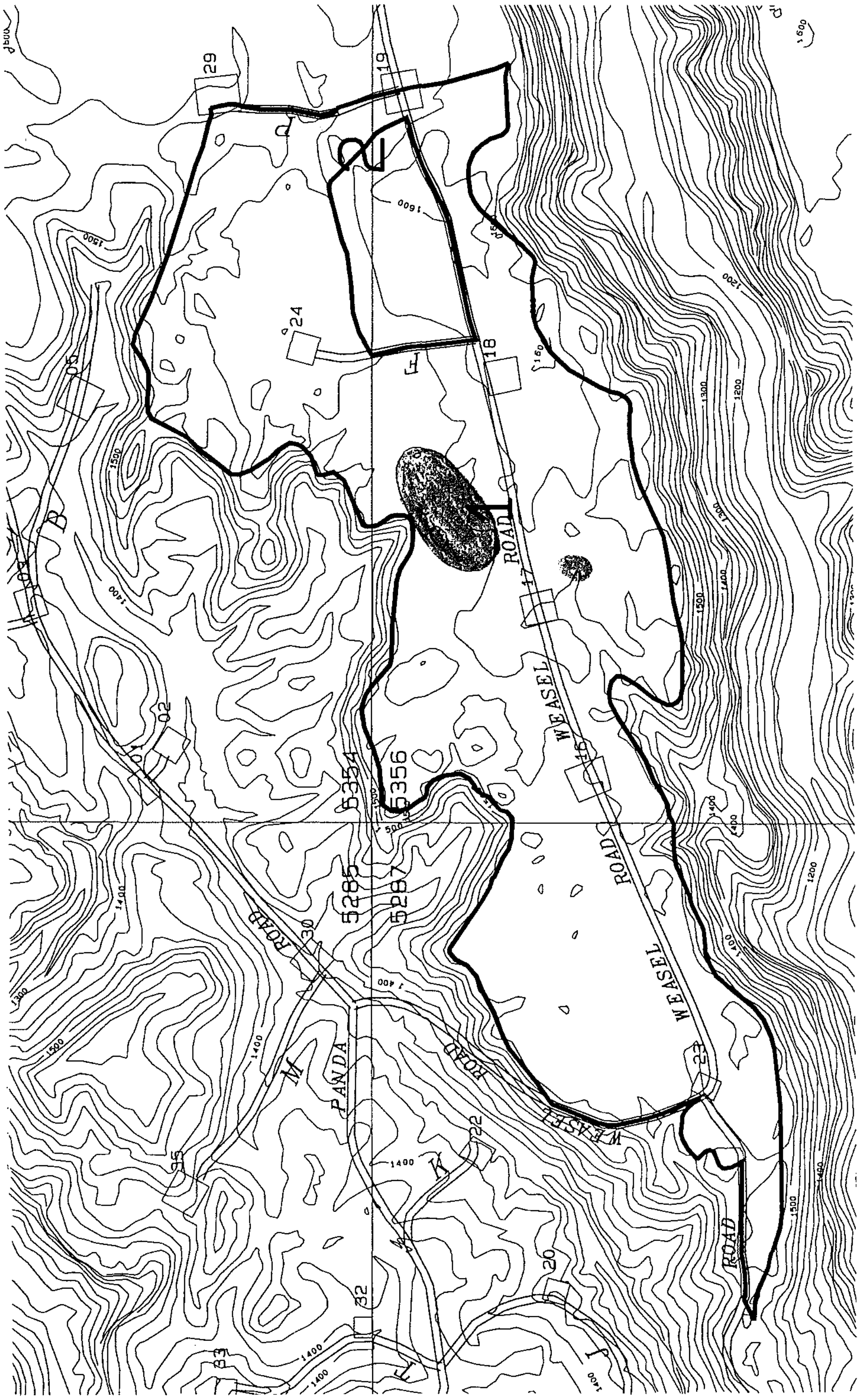


Map Seven: Timbco Two (Operator Four) Harvesting Area Location

OP_ID: 27141



Map Eight: Sampling Area Location



APPENDIX II

Forestors Vertex Operational Details

The hypsometer consists of two units - the hypsometer and the transponder. The height is computed by using two angles and one distance. The distance is measured either automatically by use of the transponder - or manually by a measuring tape. In the latter case, the measured distance must be entered into the hypsometer before the angle and height measurement can begin.

Using the Transponder

Turn the fastening pin to the active position and fasten the transponder to the selected tree. It is recommended to place the transponder at a predefined height, say 1.4 metres above the ground. With the pin in "active" position the transponder is automatically switched "ON".

The transponder should point toward the location which is approximately as far from the tree, as the tree is high, and where you can see both the transponder and the top of the tree. Start the hypsometer by pressing the ON/OFF switch. Check the "Pivot offset" and "TRP height" (typically 0.3 and 1.4). Now look through the sight and aim the red point at the transponder. The red point is focused to infinity so there is no need to close the other eye or to have the red point in the middle of the sight - you only have to position the red light on the transponder.

While aiming at the transponder, press the red button and keep it pressed until the red point disappears, then release the button. This measures the distance between the hypsometer and the transponder. Then aim at the top of the tree, the red pointer is now blinking, press the red button and keep it pressed until the light point disappears. This measures the height of the tree from the foot. Three measurements can be made to produce an average.

Calibrating the Distance

The FORESTORS VERTEX uses ultrasonic pulses to determine the distance. The speed of sound in air depends on several factors: temperature, humidity and atmospheric pressure. The built-in temperature sensor compensates for the changes in temperature. The instrument is calibrated for a "standard atmosphere" and the error will typically be +/- 1%. To increase accuracy, the FORESTORS VERTEX can be calibrated by "telling" the hypsometer what distance it is measuring. This is accomplished by using a laid out tape measure and the transponder. It is of utmost importance that the instrument has been given enough time to determine ambient temperature before attempting calibration. The instrument was checked daily and calibrated when necessary.

Technical Specifications

	Hypsometer	Transponder
Size:	113 x 52 x 47mm	40 x 48 x 100mm
Weight:	215g	120g
Battery:	2 x 1.5v alkaline	9v alkaline
Current:	25/50mA	2.5mA
Distance:	0-45m [resolution 0.1m (<20m: 0.01m)]	
Angle:	+/-100grad or +/-90deg [resolution 0.1grad]	
Height:	0-100m [resolution 0.1m]	

APPENDIX III

Bell One	Ht. To Break	Tree Ht.	X	X^2
	21	32.9	0.638298	0.407424
	30	34.4	0.872093	0.760546
	24.7	35.8	0.689944	0.476023
	18.2	35.5	0.512676	0.262837
	14.1	38.3	0.368146	0.135532
	21.4	35.5	0.602817	0.363388
	24	35.8	0.670391	0.449424
	23.1	36.3	0.636364	0.404959
	28.6	31.7	0.902208	0.81398
	21.9	30.4	0.720395	0.518969
	23	35.1	0.655271	0.42938
	27.6	34.9	0.790831	0.625414
	30.1	37	0.813514	0.661804
	18.3	36.2	0.505525	0.255555
	13.7	34.4	0.398256	0.158608
	21.5	39.2	0.548469	0.300819
	28.6	38.7	0.739018	0.546148
	17.9	39.2	0.456633	0.208513
	24	38.1	0.629921	0.396801
	25.5	34.6	0.736994	0.54316
	25.5	40.9	0.623472	0.388717
	25.2	37.1	0.679245	0.461374
	27	39.4	0.685279	0.469608
	31.9	33.1	0.963746	0.928807
	33	38.9	0.848329	0.719662
	27.5	38.1	0.721785	0.520973
	30.6	36.8	0.831522	0.691428
n = 45	31.7	35.4	0.89548	0.801885
	25.5	39.1	0.652174	0.425331
	22.8	33.3	0.684685	0.468793
	29.9	38.6	0.774611	0.600023
	26.5	35.7	0.742297	0.551005
	21.8	32.7	0.666667	0.444444
	22.3	25.3	0.881423	0.776906
	31.9	37.2	0.857527	0.735352
	22.7	36.3	0.625344	0.391056
	25.3	36.7	0.689373	0.475236
	21	39.1	0.537084	0.28846
	29.4	34	0.864706	0.747716
	25.2	34.8	0.724138	0.524376
	19	38	0.5	0.25
	24.1	39	0.617949	0.381861
	29.5	38.4	0.768229	0.590176
	25.5	34.9	0.730659	0.533863
	26.3	37.5	0.701333	0.491868
Total	1118.3	1624.3	31.15482	22.3782
Mean	24.8511111	36.09556	**0.692329**	0.497293
Sum X2	22.3782021			
(Sum X)2	970.622878			
Std. Dev.	0.13557996			
E	0.05			
t-statistic	2.704			
Sample Size	**53.76064**			

Bell Two	Ht. To Break	Tree Ht.	X	X^2
	26.3	38.2	0.688482	0.474007
	27.8	35.8	0.776536	0.603009
	28.3	33.7	0.839763	0.705201
	26.2	36.1	0.725762	0.52673
	18.1	36	0.502778	0.252785
	31.1	38.1	0.816273	0.666302
	23.8	33.9	0.702065	0.492895
	31.5	37.8	0.833333	0.694444
	31.7	34.7	0.913545	0.834564
	30.9	34.4	0.898256	0.806864
	23.3	32.4	0.719136	0.517156
	18.9	32.7	0.577982	0.334063
	28.4	31.6	0.898734	0.807723
	27.4	27.4	1	1
	16.6	35.1	0.472934	0.223667
	26.8	34.7	0.772334	0.5965
	22.6	34.5	0.655072	0.42912
	24.1	34.2	0.704678	0.496572
	25.4	36.6	0.693989	0.481621
	25.7	34	0.755882	0.571358
	24	36.3	0.661157	0.437129
	31.7	40	0.7925	0.628056
	22.3	36.6	0.60929	0.371234
	24.7	39	0.633333	0.401111
	24.4	36.2	0.674033	0.454321
	26.8	37.2	0.72043	0.51902
	27	39.2	0.688776	0.474412
n = 45	28.7	36.9	0.777778	0.604938
	25.1	27.8	0.902878	0.815188
	26.7	37.6	0.710106	0.504251
	26.8	32.2	0.832298	0.69272
	32.9	38.5	0.854545	0.730248
	29	36.6	0.79235	0.627818
	21.8	37.3	0.58445	0.341582
	29.1	36.5	0.79726	0.635624
	24.5	35.1	0.698006	0.487212
	26	35.9	0.724234	0.524515
	30.8	35.3	0.872521	0.761293
	19.4	34.7	0.559078	0.312568
	23.6	39.4	0.598985	0.358783
	25.4	37.3	0.680965	0.463714
	27.8	34.8	0.798851	0.638162
	30.6	31.6	0.968354	0.93771
	23.2	36.3	0.639118	0.408472
	24.5	37.6	0.651596	0.424577
Total	1171.7	1597.8	33.17043	25.06924
Mean	26.0377778	35.50667	**0.737121**	0.557094
Sum X^2	25.0692391			
(Sum $X)^2$	1100.27722			
Std. Dev.	0.11857431			
E	0.05			
t-statistic	2.704			
Sample Size	**41.12014**			

Timbco One	Ht. To Break	Tree Ht.	X	X^2
	34.3	36.8	0.932065	0.868746
	20.6	33.3	0.618619	0.382689
	16.7	33.5	0.498507	0.24851
	20.9	32.3	0.647059	0.418685
	7.6	30	0.253333	0.064178
	27.6	28.2	0.978723	0.9579
	19.9	27.6	0.721014	0.519862
	18.3	30	0.61	0.3721
	31.7	34.1	0.929619	0.864191
	21.8	37.3	0.58445	0.341582
	35.9	38.1	0.942257	0.887849
	30	34	0.882353	0.778547
	29.7	30.9	0.961165	0.923838
	29.9	30.1	0.993355	0.986755
	26.8	26.8	1	1
	19.7	32.3	0.609907	0.371987
	32.1	32.7	0.981651	0.963639
	27.1	27.1	1	1
	26.3	26.8	0.981343	0.963035
	26.9	28.1	0.957295	0.916414
	25.2	26.1	0.965517	0.932224
	29.5	30.2	0.976821	0.95418
	20.9	28.7	0.728223	0.530309
	30.8	35	0.88	0.7744
	26.9	32.3	0.832817	0.693585
	30.1	33.8	0.890533	0.793048
	30.7	32.2	0.953416	0.909002
n = 45	33.5	35.9	0.933148	0.870765
	28.9	31.3	0.923323	0.852525
	31.7	31.7	1	1
	31.3	32.8	0.954268	0.910628
	36.5	36.5	1	1
	27.7	31	0.893548	0.798429
	21.8	28.1	0.775801	0.601867
	30.2	30.2	1	1
	28.2	31.6	0.892405	0.796387
	22	28.6	0.769231	0.591716
	33.6	33.6	1	1
	28.8	31	0.929032	0.863101
	29.6	33.7	0.878338	0.771478
	27.5	31.8	0.86478	0.747844
	31.2	32.9	0.948328	0.899327
	28.6	35.1	0.814815	0.663923
	27.8	28.7	0.968641	0.938266
	21	34.3	0.612245	0.374844
Total	1217.8	1427.1	38.46795	34.09835
Mean	27.0622222	31.71333	**0.854843**	0.757741
Sum X^2	34.0983509			
(Sum $X)^2$	1479.78309			
Std. Dev.	0.16612442			
E	0.05			
t-statistic	2.704			
Sample Size	**80.71241**			

Timbco Two	Ht. To Break	Tree Ht.	X	X^2
	27.2	39.9	0.68170426	0.464721
	25.8	37.2	0.69354839	0.481009
	24.4	41.7	0.58513189	0.342379
	25.7	41	0.62682927	0.392915
	30.8	39.1	0.78772379	0.620509
	31.3	43.9	0.71298405	0.508346
	32.9	42.9	0.76689977	0.588135
	20.7	43.7	0.47368421	0.224377
	33.4	42.7	0.78220141	0.611839
	22.7	41.7	0.54436451	0.296333
	24.8	40.1	0.61845387	0.382485
	27	43.2	0.625	0.390625
	36.8	41	0.89756098	0.805616
	32	45.3	0.70640177	0.499003
	34.7	42.1	0.82422803	0.679352
	27.9	42	0.66428571	0.441276
	32.7	46.2	0.70779221	0.50097
	30.1	42.7	0.70491803	0.496909
	38.5	45.4	0.84801762	0.719134
	30.6	42.9	0.71328671	0.508778
	31.9	43.7	0.72997712	0.532867
	38.8	40.7	0.95331695	0.908813
	28.7	39.2	0.73214286	0.536033
	34.1	40.7	0.83783784	0.701972
	32.6	38.7	0.84237726	0.709599
	34.1	39.9	0.85463659	0.730404
	34	43.5	0.7816092	0.610913
n = 45	33.7	42.2	0.7985782	0.637727
	36.7	41.7	0.88009592	0.774569
	34.6	43.7	0.79176201	0.626887
	30.1	38.4	0.78385417	0.614427
	30.9	43.8	0.70547945	0.497701
	27.7	45	0.61555556	0.378909
	31	38.1	0.81364829	0.662024
	29.5	41.8	0.70574163	0.498071
	27.9	44.3	0.62979684	0.396644
	17	33.1	0.51359517	0.26378
	25.3	45.8	0.55240175	0.305148
	26.6	42.3	0.62884161	0.395442
	32.1	40.9	0.78484108	0.615976
	29.4	39.1	0.75191816	0.565381
	27.3	38.6	0.70725389	0.500208
	26.6	31.1	0.85530547	0.731547
	36	41.7	0.86330935	0.745303
	31.4	44.4	0.70720721	0.500142
Total	1358	1867.1	32.7861	24.3952
Mean	30.1777778	41.49111	**0.72858**	0.542116
Sum X^2	24.3951978			
$(\text{Sum } X)^2$	1074.92835			
Std. Dev.	0.10743931			
E	0.05			
t-statistic	2.704			
Sample Size	**33.75979**			

APPENDIX IV

Operator Relative Break Height Comparison
Ho: Operator 1 = Operator 2 = Operator 3 = Operator 4

N P A R 1 W A Y   P R O C E D U R E

Wilcoxon Scores (Rank Sums) for Variable RELBRK
Classified by Variable OPERATOR

OPERATOR	N	Sum of Scores	Expected Under H0	Std Dev Under H0	Mean Score
1	54	4165.5000	6102.0	416.971385	77.138889
2	45	4321.0000	5085.0	390.529483	96.022222
3	81	12775.5000	9153.0	468.635379	157.722222
4	45	4163.0000	5085.0	390.529483	92.511111

Average Scores were used for Ties

Kruskal-Wallis Test (Chi-Square Approximation)
CHISQ= 62.154 DF= 3 Prob > CHISQ= 0.0001

Bell TF120 Operator Relative Break Height Comparison
Ho: Operator 1 = Operator 2

N P A R 1 W A Y   P R O C E D U R E

Wilcoxon Scores (Rank Sums) for Variable RELBRK
Classified by Variable OPERATOR

OPERATOR	N	Sum of Scores	Expected Under H0	Std Dev Under H0	Mean Score
1	54	2444.0	2700.0	142.302495	45.2592593
2	45	2506.0	2250.0	142.302495	55.6888889

Wilcoxon 2-Sample Test (Normal Approximation)
(with Continuity Correction of .5)

S= 2506.00 Z= 1.79547 Prob > |Z| = 0.0726

T-Test approx. Significance = 0.0757

Kruskal-Wallis Test (Chi-Square Approximation)
CHISQ= 3.2363 DF= 1 Prob > CHISQ= 0.0720

Timbco T445 Operator Relative Break Height Comparison
Ho: Operator 3 = Operator 4

N P A R 1 W A Y   P R O C E D U R E

Wilcoxon Scores (Rank Sums) for Variable RELBRK
Classified by Variable OPERATOR

OPERATOR	N	Sum of Scores	Expected Under H0	Std Dev Under H0	Mean Score
3	81	6275.0	5143.50000	196.301121	77.4691358
4	45	1726.0	2857.50000	196.301121	38.3555556

Average Scores were used for Ties

Wilcoxon 2-Sample Test (Normal Approximation)
(with Continuity Correction of .5)

S= 1726.00 Z= -5.76156 Prob > |Z| = 0.0001

T-Test approx. Significance = 0.0001

Kruskal-Wallis Test (Chi-Square Approximation)
CHISQ= 33.225 DF= 1 Prob > CHISQ= 0.0001

Operator One and Three Relative Break Height Comparison
Ho: Operator 1 = Operator 3

N P A R 1 W A Y   P R O C E D U R E

Wilcoxon Scores (Rank Sums) for Variable RELBRK
Classified by Variable OPERATOR

OPERATOR	N	Sum of Scores	Expected Under H0	Std Dev Under H0	Mean Score
1	54	2216.50000	3672.0	222.548586	41.0462963
3	81	6963.50000	5508.0	222.548586	85.9691358

Average Scores were used for Ties

Wilcoxon 2-Sample Test (Normal Approximation)
(with Continuity Correction of .5)

S= 2216.50 Z= -6.53790 Prob > |Z| = 0.0001

T-Test approx. Significance = 0.0001

Kruskal-Wallis Test (Chi-Square Approximation)
CHISQ= 42.773 DF= 1 Prob > CHISQ= 0.0001

Operator One and Four Relative Break Height Comparison
Ho: Operator 1 = Operator 4

N P A R 1 W A Y P R O C E D U R E

Wilcoxon Scores (Rank Sums) for Variable RELBRK
Classified by Variable OPERATOR

OPERATOR	N	Sum of Scores	Expected Under H0	Std Dev Under H0	Mean Score
1	54	2475.0	2700.0	142.302495	45.8333333
4	45	2475.0	2250.0	142.302495	55.0000000

Wilcoxon 2-Sample Test (Normal Approximation)
(with Continuity Correction of .5)

S= 2475.00 Z= 1.57763 Prob > |Z| = 0.1147

T-Test approx. Significance = 0.1179

Kruskal-Wallis Test (Chi-Square Approximation)
CHISQ= 2.5000 DF= 1 Prob > CHISQ= 0.1138

Operator Two and Three Relative Break Height Comparison
Ho: Operator 2 = Operator 3

N P A R 1 W A Y P R O C E D U R E

Wilcoxon Scores (Rank Sums) for Variable RELBRK
Classified by Variable OPERATOR

OPERATOR	N	Sum of Scores	Expected Under H0	Std Dev Under H0	Mean Score
2	45	1822.0	2857.50000	196.274003	40.4888889
3	81	6179.0	5143.50000	196.274003	76.2839506

Average Scores were used for Ties
Wilcoxon 2-Sample Test (Normal Approximation)
(with Continuity Correction of .5)

S= 1822.00 Z= -5.27324 Prob > |Z| = 0.0001

T-Test approx. Significance = 0.0001

Kruskal-Wallis Test (Chi-Square Approximation)
CHISQ= 27.834 DF= 1 Prob > CHISQ= 0.0001

Operator Two and Four Relative Break Height Comparison
Ho: Operator 2 = Operator 4

N P A R 1 W A Y P R O C E D U R E

Wilcoxon Scores (Rank Sums) for Variable RELBRK
Classified by Variable OPERATOR

OPERATOR	N	Sum of Scores	Expected Under H0	Std Dev Under H0	Mean Score
2	45	2063.0	2047.50000	123.920337	45.8444444
4	45	2032.0	2047.50000	123.920337	45.1555556

Wilcoxon 2-Sample Test (Normal Approximation)
(with Continuity Correction of .5)

S= 2063.00 Z= 0.121046 Prob > |Z| = 0.9037

T-Test approx. Significance = 0.9039

Kruskal-Wallis Test (Chi-Square Approximation)
CHISQ= 0.01565 DF= 1 Prob > CHISQ= 0.9005

Machine Type Relative Break Height Comparison
Ho: Bell TF120=Timbco T445

N P A R 1 W A Y P R O C E D U R E

Wilcoxon Scores (Rank Sums) for Variable RELBRK
Classified by Variable OPERATOR

MACHINE	N	Sum of Scores	Expected Under H0	Std Dev Under H0	Mean Score
Bell	99	8486.5000	11187.0	484.634343	85.722222
Timbco	126	16938.5000	14238.0	484.634343	134.432540

Average Scores were used for Ties

Wilcoxon 2-Sample Test (Normal Approximation)
(with Continuity Correction of .5)

S= 8486.50 Z= -5.57121 Prob > |Z| = 0.0001

T-Test approx. Significance = 0.0001

Kruskal-Wallis Test (Chi-Square Approximation)
CHISQ= 31.050 DF= 1 Prob > CHISQ= 0.0001

APPENDIX V

Nested Analysis of Machine Type and Operator

Coefficients of Expected Mean Squares

Source	MACHINE	OPERATOR	ERROR
MACHINE	110.8800000	57.9319481	1.0000000
OPERATOR	0.0000000	53.4740260	1.0000000
ERROR	0.0000000	0.0000000	1.0000000

Nested Random Effects Analysis of Variance for Variable RELBRK

Variance Source	Degrees of Freedom	Sum of Squares	F Value	Pr > F	Error Term
TOTAL	224	5.181366			
MACHINE	1	0.598667	(Unable to be calculated due to		
OPERATOR	2	0.587013	unequal sample sizes)		
ERROR	221	3.995685			

Variance Source	Mean Square	Variance Component	Percent of Total
TOTAL	0.023131	0.025776	100.0000
MACHINE	0.598667	0.002545	9.8740
OPERATOR	0.293507	0.005151	19.9826
ERROR	0.018080	0.018080	70.1435

Mean	0.77031933
Standard error of mean	0.05241642

APPENDIX VI

Predictive Breakage Model
(DBH, CSLOPE, HEIGHT & DUM Variables)

General Linear Models Procedure
Class Level Information

Class	Levels	Values
MACHINE	2	120 445
OPERATOR	4	1 2 3 4

Number of observations in data set = 225

Dependent Variable: RELBRK

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	1.29939328	0.32484832	18.41	0.0001
Error	220	3.88197240	0.01764533		
Corrected Total	224	5.18136567			

R-Square	C.V.	Root MSE	RELBRK Mean
0.250782	17.24424	0.1328357	0.7703193

Source	DF	Type I SS	Mean Square	F Value	Pr > F
DBH	1	0.14353058	0.14353058	8.13	0.0048
CSLOPE	1	0.00268764	0.00268764	0.15	0.6967
HEIGHT	1	0.58780394	0.58780394	33.31	0.0001
DUM	1	0.56537111	0.56537111	32.04	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
DBH	1	0.00347812	0.00347812	0.20	0.6575
CSLOPE	1	0.00138408	0.00138408	0.08	0.7797
HEIGHT	1	0.59133447	0.59133447	33.51	0.0001
DUM	1	0.56537111	0.56537111	32.04	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	1.285151716	16.46	0.0001	0.07807521
DBH	-0.044690979	-0.44	0.6575	0.10066128
CSLOPE	-0.000730889	-0.28	0.7797	0.00260967
HEIGHT	-0.012551379	-5.79	0.0001	0.00216815
DUM	-0.101231131	-5.66	0.0001	0.01788390

Predictive Breakage Model

(DBH, CSLOPE, HEIGHT & DUM Variables)

General Linear Models Procedure
Class Level Information

Class	Levels	Values
MACHINE	2	120 445
OPERATOR	4	1 2 3 4

Number of observations in data set = 225

Dependent Variable: BRKHT

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	1083.2255844	270.8063961	12.75	0.0001
Error	220	4674.4070378	21.2473047		
Corrected Total	224	5757.6326222			

R-Square	C.V.	Root MSE	BRKHT Mean
0.188137	16.95465	4.6094799	27.187111

Source	DF	Type I SS	Mean Square	F Value	Pr > F
DBH	1	15.52653368	15.52653368	0.73	0.3936
CSLOPE	1	0.03252980	0.03252980	0.00	0.9688
HEIGHT	1	423.61481648	423.61481648	19.94	0.0001
DUM	1	644.05170444	644.05170444	30.31	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
DBH	1	1.83604919	1.83604919	0.09	0.7691
CSLOPE	1	0.70357016	0.70357016	0.03	0.8558
HEIGHT	1	420.41778235	420.41778235	19.79	0.0001
DUM	1	644.05170444	644.05170444	30.31	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	17.30811300	6.39	0.0001	2.70925714
DBH	-1.02680910	-0.29	0.7691	3.49300717
CSLOPE	-0.01647877	-0.18	0.8558	0.09055723
HEIGHT	0.33466893	4.45	0.0001	0.07523619
DUM	-3.41670629	-5.51	0.0001	0.62058204

Predictive Breakage Model
(DBH, CSLOPE, HEIGHT & DUM Variables)

General Linear Models Procedure
Class Level Information

Class	Levels	Values
MACHINE	2	120 445
OPERATOR	4	1 2 3 4

Number of observations in data set = 225

Dependent Variable: DIA

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	0.68869278	0.17217320	26.81	0.0001
Error	220	1.41295744	0.00642253		
Corrected Total	224	2.10165022			

R-Square	C.V.	Root MSE	DIA Mean
0.327691	48.95252	0.0801407	0.1637111

Source	DF	Type I SS	Mean Square	F Value	Pr > F
DBH	1	0.22547121	0.22547121	35.11	0.0001
CSLOPE	1	0.00031466	0.00031466	0.05	0.8250
HEIGHT	1	0.29338142	0.29338142	45.68	0.0001
DUM	1	0.16952549	0.16952549	26.40	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
DBH	1	0.05926136	0.05926136	9.23	0.0027
CSLOPE	1	0.00004496	0.00004496	0.01	0.9334
HEIGHT	1	0.29474615	0.29474615	45.89	0.0001
DUM	1	0.16952549	0.16952549	26.40	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	-.2701238141	-5.73	0.0001	0.04710332
DBH	0.1844732285	3.04	0.0027	0.06072965
CSLOPE	0.0001317256	0.08	0.9334	0.00157443
HEIGHT	0.0088613304	6.77	0.0001	0.00130806
DUM	0.0554325414	5.14	0.0001	0.01078948

APPENDIX VII

Predictive Breakage Model
(HEIGHT and DUM Variables)

General Linear Models Procedure
Class Level Information

Class	Levels	Values
MACHINE	2	120 445
OPERATOR	4	1 2 3 4

Number of observations in data set = 225

Dependent Variable: RELBRK

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1.29479693	0.64739846	36.98	0.0001
Error	222	3.88656875	0.01750707		
Corrected Total	224	5.18136567			

R-Square	C.V.	Root MSE	RELBRK Mean
0.249895	17.17655	0.1323143	0.7703193

Source	DF	Type I SS	Mean Square	F Value	Pr > F
HEIGHT	1	0.72148921	0.72148921	41.21	0.0001
DUM	1	0.57330772	0.57330772	32.75	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
HEIGHT	1	0.69612962	0.69612962	39.76	0.0001
DUM	1	0.57330772	0.57330772	32.75	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	1.273326525	17.33	0.0001	0.07347010
HEIGHT	-0.012868301	-6.31	0.0001	0.00204072
DUM	-0.101710632	-5.72	0.0001	0.01777375

Predictive Breakage Model
(HEIGHT & DUM Variables)

General Linear Models Procedure
Class Level Information

Class	Levels	Values
MACHINE	2	120 445
OPERATOR	4	1 2 3 4

Number of observations in data set = 225

General Linear Models Procedure

Dependent Variable: BRKHT

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1080.8235915	540.4117958	25.65	0.0001
Error	222	4676.8090307	21.0667073		
Corrected Total	224	5757.6326222			

R-Square	C.V.	Root MSE	BRKHT Mean
0.187720	16.88244	4.5898483	27.187111

Source	DF	Type I SS	Mean Square	F Value	Pr > F
HEIGHT	1	429.68697205	429.68697205	20.40	0.0001
DUM	1	651.13661945	651.13661945	30.91	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
HEIGHT	1	450.58221748	450.58221748	21.39	0.0001
DUM	1	651.13661945	651.13661945	30.91	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	17.03665677	6.68	0.0001	2.54860357
HEIGHT	0.32738833	4.62	0.0001	0.07079042
DUM	-3.42774511	-5.56	0.0001	0.61655353

Predictive Breakage Model
(DBH, CSLOPE, HEIGHT & DUM Variables)

General Linear Models Procedure
Class Level Information

Class	Levels	Values
MACHINE	2	120 445
OPERATOR	4	1 2 3 4

Number of observations in data set = 225

General Linear Models Procedure

Dependent Variable: DIA

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	0.68864783	0.22954928	35.90	0.0001
Error	221	1.41300240	0.00639368		
Corrected Total	224	2.10165022			

R-Square	C.V.	Root MSE	DIA Mean
0.327670	48.84242	0.0799605	0.1637111

Source	DF	Type I SS	Mean Square	F Value	Pr > F
DBH	1	0.22547121	0.22547121	35.26	0.0001
HEIGHT	1	0.29367757	0.29367757	45.93	0.0001
DUM	1	0.16949904	0.16949904	26.51	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
DBH	1	0.05929994	0.05929994	9.27	0.0026
HEIGHT	1	0.29510776	0.29510776	46.16	0.0001
DUM	1	0.16949904	0.16949904	26.51	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	-.2699412603	-5.75	0.0001	0.04694693
DBH	0.1841429115	3.05	0.0026	0.06046488
HEIGHT	0.0088640422	6.79	0.0001	0.00130472
DUM	0.0554272725	5.15	0.0001	0.01076503

APPENDIX VIII

Predictive Breakage Model
(DBH, CSLOPE, HEIGHT & DUM Variables)

General Linear Models Procedure
Class Level Information

Class	Levels	Values
MACHINE	2	120 445
OPERATOR	4	1 2 3 4

Number of observations in data set = 154

Dependent Variable: RELBRK

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	1.39602740	0.34900685	35.75	0.0001
Error	149	1.45451114	0.00976182		
Corrected Total	153	2.85053855			

R-Square	C.V.	Root MSE	RELBRK Mean
0.489742	12.39062	0.0988019	0.7973932

Source	DF	Type I SS	Mean Square	F Value	Pr > F
DBH	1	0.08265048	0.08265048	8.47	0.0042
CSLOPE	1	0.01437191	0.01437191	1.47	0.2269
HEIGHT	1	0.64940085	0.64940085	66.52	0.0001
DUM	1	0.64960417	0.64960417	66.55	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
DBH	1	0.01487680	0.01487680	1.52	0.2190
CSLOPE	1	0.02056676	0.02056676	2.11	0.1487
HEIGHT	1	0.76241855	0.76241855	78.10	0.0001
DUM	1	0.64960417	0.64960417	66.55	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	1.406062675	20.95	0.0001	0.06712742
DBH	0.113384550	1.23	0.2190	0.09184689
CSLOPE	0.004649625	1.45	0.1487	0.00320332
HEIGHT	-0.017051734	-8.84	0.0001	0.00192947
DUM	-0.131380935	-8.16	0.0001	0.01610547

Predictive Breakage Model
(HEIGHT & DUM Variables)

General Linear Models Procedure
Class Level Information

Class	Levels	Values
MACHINE	2	120 445
OPERATOR	4	1 2 3 4

Number of observations in data set = 154

Dependent Variable: BRKHT

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	969.18353748	242.29588437	18.90	0.0001
Error	149	1910.59496902	12.82278503		
Corrected Total	153	2879.77850649			

R-Square	C.V.	Root MSE	BRKHT Mean
0.336548	12.72369	3.5808917	28.143506

Source	DF	Type I SS	Mean Square	F Value	Pr > F
DBH	1	55.74060380	55.74060380	4.35	0.0388
CSLOPE	1	30.86074659	30.86074659	2.41	0.1229
HEIGHT	1	168.67309774	168.67309774	13.15	0.0004
DUM	1	713.90908935	713.90908935	55.68	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
DBH	1	19.95416867	19.95416867	1.56	0.2142
CSLOPE	1	27.76388943	27.76388943	2.17	0.1433
HEIGHT	1	112.45039127	112.45039127	8.77	0.0036
DUM	1	713.90908935	713.90908935	55.68	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	20.55916022	8.45	0.0001	2.43290841
DBH	4.15255986	1.25	0.2142	3.32881962
CSLOPE	0.17083435	1.47	0.1433	0.11609840
HEIGHT	0.20708674	2.96	0.0036	0.06992991
DUM	-4.35541358	-7.46	0.0001	0.58371268

Predictive Breakage Model
(DBH, CSLOPE, HEIGHT & DUM Variables)

General Linear Models Procedure
Class Level Information

Class	Levels	Values
MACHINE	2	120 445
OPERATOR	4	1 2 3 4

Number of observations in data set = 154

Dependent Variable: DIA

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	0.67036307	0.16759077	45.21	0.0001
Error	149	0.55232816	0.00370690		
Corrected Total	153	1.22269123			

R-Square	C.V.	Root MSE	DIA Mean
0.548268	41.87105	0.0608843	0.1454091

Source	DF	Type I SS	Mean Square	F Value	Pr > F
DBH	1	0.12763385	0.12763385	34.43	0.0001
CSLOPE	1	0.00266920	0.00266920	0.72	0.3975
HEIGHT	1	0.33308814	0.33308814	89.86	0.0001
DUM	1	0.20697188	0.20697188	55.83	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
DBH	1	0.00405455	0.00405455	1.09	0.2973
CSLOPE	1	0.00465563	0.00465563	1.26	0.2642
HEIGHT	1	0.37781342	0.37781342	101.92	0.0001
DUM	1	0.20697188	0.20697188	55.83	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	-.3442091384	-8.32	0.0001	0.04136567
DBH	0.0591929769	1.05	0.2973	0.05659845
CSLOPE	-.0022121986	-1.12	0.2642	0.00197397
HEIGHT	0.0120035722	10.10	0.0001	0.00118899
DUM	0.0741589574	7.47	0.0001	0.00992461

APPENDIX IX

Predictive Breakage Model
(HEIGHT & DUM Variables)

General Linear Models Procedure
Class Level Information

Class	Levels	Values
MACHINE	2	120 445
OPERATOR	4	1 2 3 4

Number of observations in data set = 154

General Linear Models Procedure

Dependent Variable: RELBRK

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1.36144782	0.68072391	69.03	0.0001
Error	151	1.48909072	0.00986153		
Corrected Total	153	2.85053855			

R-Square	C.V.	Root MSE	RELBRK Mean
0.477611	12.45373	0.0993052	0.7973932

Source	DF	Type I SS	Mean Square	F Value	Pr > F
HEIGHT	1	0.72454991	0.72454991	73.47	0.0001
DUM	1	0.63689792	0.63689792	64.58	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
HEIGHT	1	0.79947650	0.79947650	81.07	0.0001
DUM	1	0.63689792	0.63689792	64.58	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	1.429026726	21.98	0.0001	0.06500490
HEIGHT	-0.016076079	-9.00	0.0001	0.00178546
DUM	-0.129517822	-8.04	0.0001	0.01611635

Predictive Breakage Model
(HEIGHT & DUM Variables)

General Linear Models Procedure
Class Level Information

Class	Levels	Values
MACHINE	2	120 445
OPERATOR	4	1 2 3 4

Number of observations in data set = 154

General Linear Models Procedure

Dependent Variable: BRKHT

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	922.62804062	461.31402031	35.59	0.0001
Error	151	1957.15046587	12.96126136		
Corrected Total	153	2879.77850649			

R-Square	C.V.	Root MSE	BRKHT Mean
0.320382	12.79221	3.6001752	28.143506

Source	DF	Type I SS	Mean Square	F Value	Pr > F
HEIGHT	1	224.79089584	224.79089584	17.34	0.0001
DUM	1	697.83714478	697.83714478	53.84	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
HEIGHT	1	182.40231503	182.40231503	14.07	0.0003
DUM	1	697.83714478	697.83714478	53.84	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	21.40028250	9.08	0.0001	2.35666358
HEIGHT	0.24282447	3.75	0.0003	0.06472930
DUM	-4.28717942	-7.34	0.0001	0.58427628

Predictive Breakage Model
(HEIGHT & DUM Variables)

General Linear Models Procedure
Class Level Information

Class	Levels	Values
MACHINE	2	120 445
OPERATOR	4	1 2 3 4

Number of observations in data set = 154

General Linear Models Procedure

Dependent Variable: DIA

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.66142705	0.33071353	88.97	0.0001
Error	151	0.56126418	0.00371698		
Corrected Total	153	1.22269123			

R-Square	C.V.	Root MSE	DIA Mean
0.540960	41.92795	0.0609671	0.1454091

Source	DF	Type I SS	Mean Square	F Value	Pr > F
HEIGHT	1	0.44711568	0.44711568	120.29	0.0001
DUM	1	0.21431138	0.21431138	57.66	0.0001

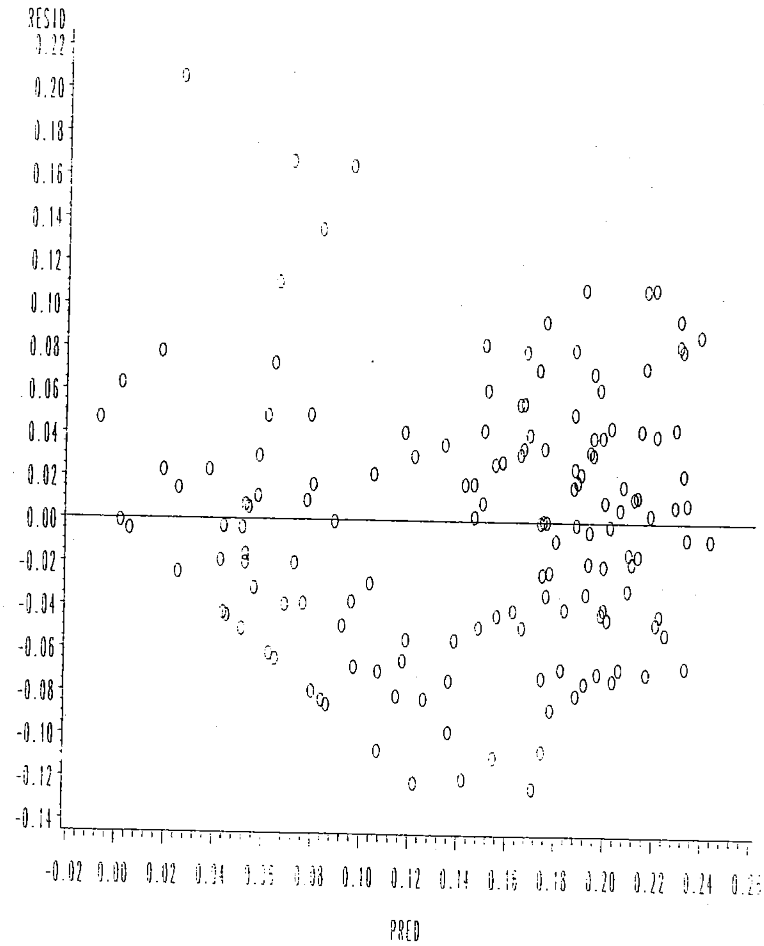
Source	DF	Type III SS	Mean Square	F Value	Pr > F
HEIGHT	1	0.48066589	0.48066589	129.32	0.0001
DUM	1	0.21431138	0.21431138	57.66	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	-.3330178218	-8.34	0.0001	0.03990884
HEIGHT	0.0124651905	11.37	0.0001	0.00109616
DUM	0.0751306646	7.59	0.0001	0.00989441

APPENDIX X

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	-.3330178218	-8.34	0.0001	0.03990884
HEIGHT	0.0124651905	11.37	0.0001	0.00109616
DUM	0.0751306646	7.59	0.0001	0.00989441

Figure I: Residuals Versus Predicted for DIA Model Two.



Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT	1.429026726	21.98	0.0001	0.06500490
HEIGHT	-0.016076079	-9.00	0.0001	0.00178546
DUM	-0.129517822	-8.04	0.0001	0.01611635

Figure II: Residuals Versus Predicted for RELBRK Model Two